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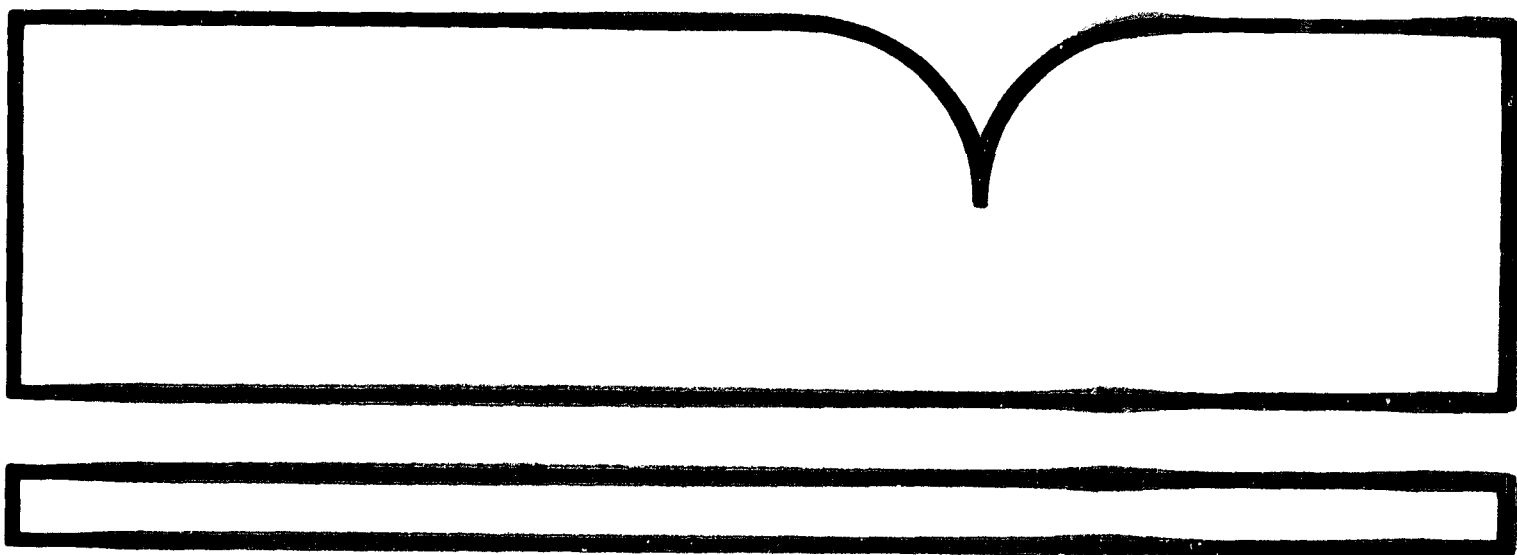
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Plasmas and Fluids

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## PHYSICS THROUGH THE 1990s



# Plasmas and Fluids

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**PHYSICS THROUGH THE 1990s**

# **Plasmas and Fluids**

**Panel on the Physics of  
Plasmas and Fluids**

**Physics Survey Committee**

**Board on Physics and Astronomy**

**Commission on Physical Sciences,  
Mathematics, and Resources**

**National Research Council**

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## Preface

This survey of plasma physics and fluid physics briefly describes present activities and recent major accomplishments. It also identifies research areas that are likely to lead to advances during the next decade.

Plasma physics is divided into three major areas: general plasma physics, fusion plasma confinement and heating, and space and astrophysical plasmas. Fluid physics is treated as one topic, although it is an extremely diverse research field ranging from biological fluid dynamics to ship and aircraft performance to geological fluid dynamics. Subpanels, chosen for their technical expertise and scientific breadth, reviewed each of the four areas. The entire survey was coordinated and supervised by an Executive Committee, which is also responsible for the Executive Summary of this volume. Wherever possible, input from recent Advisory Committees was used, e.g., from the Magnetic Fusion Advisory Committee, the Space Science Board, and the Astronomy Survey Committee.

This volume is organized as follows: Chapter 1 is an Introduction and Executive Summary that outlines (a) major findings and recommendations; (b) significant research accomplishments during the past decade and likely areas of future research emphasis; and (c) a brief summary of present funding levels, manpower resources, and institutional involvement. The subpanel reports constitute Chapters 2-5 of this volume, including Fluid Physics (Chapter 2), General Plasma Physics

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(Chapter 3), Fusion Plasma Confinement and Heating (Chapter 4), and Space and Astrophysical Plasmas (Chapter 5).

An important conclusion of this survey is that both plasma physics and fluid physics are scientifically and intellectually well developed, and both areas are broad subdisciplines of physics. We therefore recommend that future physics surveys have separate volumes on the physics of plasmas and the physics of fluids.

Finally, we are grateful for the technical contributions and conscientious efforts of the individual subpanel members. In addition, we wish to thank the many expert readers who have reviewed this report and provided useful suggestions that improved the document. The readers include Stirling Colgate, John Deutch, Herman Feshbach, George Field, William Fowler, Edward Frieman, Harold Furth, Hans Griem, Robert Gross, Donald Kerst, Hans Liepmann, Jeremiah Ostriker, Eugene Parker, David Pines, Marshall Rosenbluth, Ascher Shapiro, Joseph Smagorinsky, and Edward Stone. We appreciate their valuable contributions.

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## Introduction and Executive Summary

### GENERAL FINDINGS AND RECOMMENDATIONS

#### Findings

The Panel has the following general findings concerning plasma physics and fluid physics:

- In each area reviewed by the Panel, the level of basic understanding increased significantly during the past decade.
- Although most plasma and fluid research is motivated by applications such as defense, fusion, space, communications, and atmospheric modeling, the associated fundamental physics is at the very forefront of knowledge and is characterized by high intellectual challenge.
- All matter under physical conditions with energies exceeding 1 electron volt per atom above the ground state involves plasma-physics phenomena. Plasma physics combines concepts from electromagnetism, fluid physics, statistical mechanics, and atomic physics into a unified methodology for the study and practical use of the nonlinear collective interactions of charged particles with one another and with electric and magnetic fields.
- The most important applications of plasma physics are to fusion and space research, which have stimulated many recent advances in plasma science. Other applications include new types of particle

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- The most important applications of plasma physics are to fusion and space research, which have stimulated many recent advances in plasma science. Other applications include new types of particle

accelerators and coherent radiation sources, isotope separation, and astrophysics.

- The technology needed to study hot plasmas in the laboratory and natural plasmas in space has been developed largely over the past 25 years. As a result, plasma physics has become a well-developed scientific discipline.

- The 1970s saw the extensive development of coherent and turbulent nonlinear plasma physics, which is proving to be fundamental. Many nonlinear concepts and mathematical methods developed in plasma physics, such as solitons and stochasticity, have found applications in other areas of physics.

- The above theoretical advances aided by rapid developments in precision plasma diagnostics and data-acquisition techniques have led to significant technical advances in the laboratory. These include, for example, the demonstration of rf current drive in tokamaks, observation of plasma solitons and cavitons, and magnetic braiding and the development of new coherent radiation sources such as the free-electron laser, the gyrotron, and the x-ray laser.

- The increasing precision of measurements, numerical modeling, and theory applied to space plasma problems amount to a revolution in technique relative to 10 years ago. The study of space plasmas has become one of the primary theoretical and experimental arenas for basic plasma research.

- The concepts and techniques of plasma physics find widespread use in plasma physics, atmospheric science, oceanography, solid-earth geophysics, astrophysics, biology, and medicine; in problems in laser physics, combustion, and pollution control; and in the engineering of transportation and defense systems, among others.

- The understanding of turbulent fluid motion and the ability to control it have increased dramatically during the past decade. The transition from organized to chaotic fluid flow has become a principal arena for testing recent conceptual advances in nonlinear mechanics.

- The effectiveness of fluid-physics and plasma-physics research is being revolutionized by the use of large-scale numerical computations to investigate and solve previously intractable theoretical problems, as well as to analyze and correlate large arrays of data.

### Recommendations

In addition to the specific recommendations summarized in the following chapters, the Panel makes the following general recommendations:

## 2 PLASMAS AND FLUIDS

accelerators and coherent radiation sources, isotope separation, and astrophysics.

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- The effectiveness of fluid-physics and plasma-physics research is being revolutionized by the use of large-scale numerical computations to investigate and solve previously intractable theoretical problems, as well as to analyze and correlate large arrays of data.

### Recommendations

In addition to the specific recommendations summarized in the following chapters, the Panel makes the following general recommendations:

- To advance our understanding of fusion and space plasmas, and to maintain and extend U.S. excellence in plasma physics, we recommend that the federal government proceed with the next generation of major projects in fusion and space research that are identified later in this report and in other reports referenced herein.

- To enhance progress in fluid-physics research, we recommend two national research initiatives: one would develop and deploy the simultaneous, multipoint flow instrumentation described later in this report; the other would expand programs for research access to major computational and experimental fluid-physics facilities.

- In view of the significant advances in plasma physics and fluid physics during the past decade, we recommend a renewed commitment by the federal government to basic research in these subjects. An adequate level of basic research, free from short-term, application-oriented goals, should be established in order to provide the foundations for future scientific advances and new technologies.

In addition, the Panel makes the following recommendation to the academic community:

- In view of the increasing precision of the experimental and theoretical techniques of plasma and fluid physics, and their many applications, we strongly recommend that senior-level courses in plasma physics and fluid physics become a required part of university physics curricula.

## INTRODUCTION

### The Emergence of Plasma Physics

With the rise of electrical science in the nineteenth century came intimations of what are recognized today to be plasma effects. In the 1830s, Michael Faraday created electrical discharges to study the chemical transformations induced by electrical currents. These discharges exhibited unusual structured glows that were manifestations of a new state of matter. It was impossible to go further until the discovery of the electron by J.J. Thomson in 1895 and the elucidation of the atomic theory of matter by N. Bohr, E. Rutherford, and others shortly thereafter. By the early twentieth century, the subjects of electromagnetism, fluid mechanics, statistical mechanics, and atomic physics had been clearly defined. These would eventually be assembled into a unified methodology for the study of the nonlinear collective interactions of electrically charged particles with one another and with

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electric and magnetic fields, i.e., plasma physics. The realization that plasma is the fourth physical state of matter was a major achievement reserved for twentieth-century physics.

Advances in understanding plasmas in the laboratory, in space, and in astrophysics occurred in parallel throughout the twentieth century. In the 1920s, I. Langmuir discovered collective plasma oscillations in the laboratory, and G. Breit and M. Tuve first reflected radio waves from the ionosphere—the very edge of space. Between 1930 and 1950, the foundations of plasma physics were created, largely as a by-product of ionospheric, solar-terrestrial, and astrophysical research, motivated by such diverse concerns as understanding how radio waves propagate in the ionosphere, how solar activity leads to auroral displays and magnetic storms on Earth, and the role of magnetic fields in the behavior of stars, galaxies, and the interstellar medium. H. Alfvén, E. Appleton, S. Chandrasekhar, S. Chapman, T. Cowling, M. Saha, L. Spitzer, and many others contributed to this research. During this period, laboratory gas-discharge experiments multiplied in number and efficacy. In 1946, L. Landau developed the first theory of the interaction between waves and resonant particles in a plasma without collisions. By the 1950s, it was clear that the collision-free nature of hot plasmas was an essential property that highlights the collective interactions fundamental to plasmas.

Modern plasma physics began in the 1950s. Two events symbolizing the deeper intellectual currents of those years were the first successful launch of an artificial Earth satellite by the Soviet Union and the revelation, through declassification, that both the United States and the Soviet Union had been trying to harness the energy source of the Sun—thermonuclear fusion—for peaceful purposes. Then, as now, the obstacles to achieving controlled fusion lay not in our ignorance of nuclear physics, but of plasma physics. In 1958, the terrestrial radiation belts were discovered and in 1960, the solar wind, both by spacecraft. These discoveries showed that our exploration and future understanding of the Earth and Sun's space environment would also be couched in terms of plasma physics.

Two powerful motivations stimulated the growth of plasma physics after 1960. Fusion research seeks a source of energy accessible to human use that will last for a time comparable with the present age of the Earth. Space research seeks useful comprehension of nature's processes on a global and, indeed, solar-system scale, in recognition of Man's dependence on his environment, as well as his curiosity about the cosmos.

The international effort to achieve controlled thermonuclear fusion has been the primary stimulus to the development of laboratory plasma physics. As early as 1958, the theta-pinch configuration produced fusion temperatures at high plasma densities. However, the energy confinement time was orders of magnitude lower than that required for net energy production. The simultaneous achievement of high temperatures, densities, and confinement times—similar to the plasma conditions at the centers of stars—required significant improvements in forming and understanding plasmas confined by magnetic fields or by inertial techniques. It became possible to diagnose fusion plasmas with increasing precision, and theoretical plasma physics was stimulated to explain observations made possible by more detailed and complete measurements. The technology needed to create fusion plasma conditions in the laboratory—high magnetic field, large-volume superconducting magnets, intense energetic neutral beams, powerful lasers, vacuum and surface techniques, and high-power radio-frequency sources spanning a wide range of frequencies—was systematically assembled. The scientific feasibility of controlled fusion will likely be demonstrated in the coming decade, an event that we expect will invigorate research in plasma physics, just as the emergence of the tokamak as an attractive confinement approach in the late 1960s led to strong growth of the fusion program in the 1970s.

As the science and related experimental techniques developed, other applications of plasma physics came into view. One example, among many, is the free-electron laser. The free-electron laser, which can generate coherent radiation from microwaves to optical frequencies and perhaps even into the x-ray range, will find applications in many branches of physics, other sciences, industry, and medicine. Using collective plasma effects, it may also be possible to create a new generation of accelerators, such as the beat-wave accelerator, operating at the frontiers of high-energy particle physics.

A new and challenging application of plasma physics is to the separation of stable and unstable isotopes, for nuclear fuels, for medical research and diagnostics, for agricultural research, for tracking the motion of environmental pollutants, and for other uses. Many subtle problems of plasma physics, plasma chemistry, and plasma-surface interactions arise in isotope-separation research.

It is significant that the same discipline of physics—plasma physics—defines the basic language now used both in fusion research and in solar-system plasma physics. The experimental diagnosis and theoretical interpretation of many space plasma processes now match in precision the best of current laboratory practice. As a result, the study



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of space plasmas has become one of the primary motivations and experimental arenas for basic plasma research. Moreover, the plasma phenomena in the solar system have proven to be examples of general astrophysical processes. Not only does plasma physics describe both solar-system and astrophysical phenomena, but the solar system has become a laboratory in which astrophysical processes of great generality can be studied in situ.

The study of plasmas beyond the solar system has developed more slowly than space plasma physics for a fundamental reason: the microscopic plasma processes that regulate the behavior of distant astrophysical systems cannot be observed directly, as they can in space and in the laboratory. Now, however, the modern theoretical and computational techniques developed to understand fusion, laboratory, and space measurements have opened the door to modeling of the plasmas in the still larger and more exotic environments of astrophysics, ranging from stellar atmospheres to quasars.

Such numerical modeling, which is at the cutting edge of computer physics, is applied to statistical mechanics, nonlinear dynamics, fluid turbulence, and elementary-particle physics, as well as to plasma physics. In plasma physics, it has made quantitative the study of complex magnetohydrodynamic systems, and it has clarified the nonlinear collective processes that regulate plasma transport in such systems.

Developed scientific disciplines are characterized by deep philosophical motivations, a unified body of powerful theoretical and experimental techniques, and a wide range of applications. It is our conviction that with the growing integration of laboratory, fusion, space, and astrophysical plasma research, plasma physics is becoming a well-developed scientific discipline. When a scientific discipline matures, technological innovation follows. Plasma physics, the only major branch of physics to come largely into being in the past generation, is just beginning to have its impact.

### Classification of Plasmas

The plasmas encountered in nature and studied in the laboratory can be classified as tenuous or dense, classical or quantum. Given the wide range of plasma types and phenomena examined in this report, it is useful to display this diversity in a single plot of plasma temperature  $T$  (in kelvins) versus density  $n$  (per cubic centimeter) as shown in Figure 1.1. Evidently, plasmas range from the extremely hot, relativistic, classical, tenuous plasmas encountered in the magnetospheres of

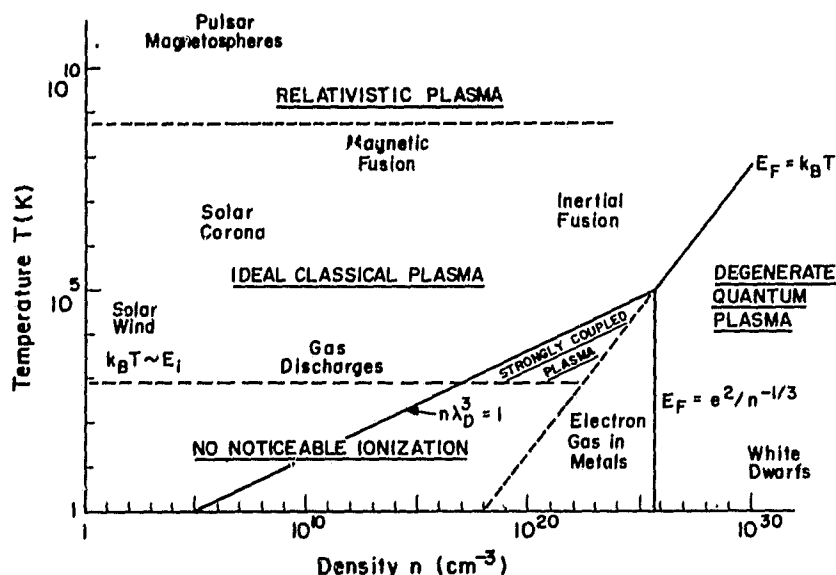


FIGURE 1.1 Classification of plasmas by temperature and density.

pulsars to the extremely dense, cold, degenerate quantum electron plasmas in white dwarfs.

As a guide to Figure 1.1, we consider a plasma with average number density  $n$  and mean kinetic energy  $(3/2)k_B T$  per particle. (Here,  $k_B$  is Boltzmann's constant.) The average distance between neighboring charged particles is  $r_0 \sim n^{-1/3}$ . Therefore, the average Coulomb interaction energy between neighboring particles is  $\langle \phi \rangle \sim e^2/n^{-1/3}$ , where  $e$  is the electron charge. Assuming a warm plasma with  $k_B T$  exceeding the ionization energy  $E_i$  in Figure 1.1, then the plasma is classified as an *ideal classical plasma* provided  $k_B T \gg e^2/n^{-1/3}$ , i.e., provided the thermal kinetic energy is large in comparison with the average Coulomb interaction energy. If both sides of this inequality are raised to the 3/2 power, this condition can also be expressed as  $n\lambda_D^3 \gg 1$ , where the Debye length  $\lambda_D = (k_B T / 4\pi n e^2)^{1/2}$  is the characteristic shielding distance of the Coulomb interaction potential in a plasma. It is evident from Figure 1.1 that an extensive region of  $(n, T)$  parameter space is located above the curves  $n\lambda_D^3 = 1$  and  $k_B T \sim E_i$ , corresponding to ideal classical plasmas. Although they have widely different densities and temperatures, such classical plasmas include pulsar magnetospheres and other astrophysical systems, the solar corona, the

solar wind, and planetary magnetospheres, as well as a wide range of laboratory plasmas characteristic of magnetic and inertial confinement fusion.

As the plasma density is increased, the average distance between neighboring particles becomes very small, and quantum effects become important when  $n^{-1/3}$  is comparable to the thermal de Broglie wavelength  $\hbar/m_e(2k_B T_e/m_e)^{1/2}$  of an electron. The characteristic scale of electron kinetic energy in such a quantum plasma is the Fermi energy  $E_F \sim \hbar^2(3\pi^2 n)^{2/3}/2m_e$ , where  $2\pi\hbar$  is Planck's constant and  $m_e$  is the electron mass. Referring to Figure 1.1, quantum effects become important when  $E_F > k_B T$ , i.e., when the Fermi energy exceeds the classical thermal energy  $k_B T$ . If the Fermi energy  $E_F$  also exceeds the average classical Coulomb interaction energy  $e^2/n^{-1/3}$ , the quantum plasma is *ideal* and weak-interaction models can be used to describe such degenerate quantum systems. An example is the degenerate electron gas in white dwarfs. On the other hand, in the region  $k_B T < E_F < e^2/n^{-1/3}$ , which includes the electron gas in metals in Figure 1.1, the quantum plasma is *nonideal*.

Finally, the small triangular region in Figure 1.1 bounded by  $n\lambda_D^3 = 1$ ,  $k_B T \sim E_i$ , and  $k_B T = E_F$  is referred to as *strongly coupled plasma*. Such plasmas are classical (since  $k_B T > E_F$ ), but the Coulomb interactions are strong since  $e^2/n^{-1/3}$  is typically larger than  $k_B T$  in this region. Unlike ideal classical plasmas (where  $e^2/n^{-1/3} \ll k_B T$ ), the correlations due to Coulomb interactions are strong, and such systems are modeled by numerical simulation on high-speed computers.

### Fluid Physics\*

Fluid physics, which is among the oldest branches of the physical sciences, continues to fascinate scientists and engineers with an eclectic collection of elegant problems. Our need to understand the world of flow around us, encompassing the nature of transport across biological membranes to the appearance of solitary waves in planetary atmospheres, remains a constant stimulation and adventure.

Fluid motion, which can exhibit the apparent randomness of turbulent flow as well as much larger-scale coherent structures, provides one

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\*The term "fluid physics" is appropriate in the context of this report. However, owing to the broad range of interests of its practitioners, it uses several names, each of which is proper in its own context. Therefore, terms such as "fluid mechanics," "gasdynamics," and "biofluid mechanics" are often used to describe special branches.

of the premier testing grounds for new developments in nonlinear dynamics. Wavelike fluid-mechanic teleconnections transmit information about the Earth's tropical oceans over vast distances to alter patterns of global atmospheric circulation. Swimming creatures are governed by the laws of efficient underwater travel, providing insights into the evolutionary pathways stimulated by changing environments or vacant biological niches.

In common with many other branches of physics, fluid physics also finds a driving force in the existence of important problems in engineering. The pacing element for advances in many applications such as the efficiency of flight, the effectiveness of heat engines, and the productivity of chemical processing systems is our understanding of the fundamentals of fluid motion. There are striking examples in the machines of engineering as they exist today, compared with even the recent past, that measure the magnitude of the advances in our understanding of fluid physics. As it is beyond the scope of this report to delineate all of these advances, only a few are mentioned as examples.

The modern transport plane, with swept wings and quiet engines, reflects the progress in the last few decades of our understanding of high-speed flows. These configurations have been derived by a combination of originally empirical and, more recently, theoretical and conceptual constructs made possible by advances in our understanding of the physics of flow. The gas turbine engine of today, although superficially similar to its historical counterpart, includes major improvements made possible by extensive efforts in fluid physics. The increased fundamental knowledge of combustion and heat transfer, which was obtained with so much difficulty through research, has led to lower exhaust pollution and longer life of the critical engine components. Today's chemical engineering plants have a throughput and an efficiency increase manyfold over those of only a decade ago, brought about by careful analysis of fluid mixing and heat transfer. These examples illustrate that basic knowledge in fluid physics moves quickly from research in flow physics to application because of the intense competitiveness of today's technological society.

In summary, fluid physics remains intellectually stimulating owing to the elegance, widespread natural occurrence, and importance of its problems. In addition, new levels of understanding of complex phenomena have further vitalized this field. Much of this understanding has been created in the last decade by the development of powerful new tools that enable us to investigate the nature of complex phenomena that heretofore appeared to be intractable mysteries. Thus, the study of turbulence, complex high-speed flows, biological flows, and

geological phenomena has been paced by new developments in powerful computational and instrumentation techniques. We look forward to the next decade as a time of excitement and adventure. The implications of mastering many important practical problems so necessary for the well-being of the nation and the world serve as further stimulus.

### PRINCIPAL FINDINGS AND RECOMMENDATIONS

We summarize here selected major findings and recommendations that pertain to the areas reviewed by the Panel on the Physics of Plasmas and Fluids.

#### General Plasma Physics

- The fundamental studies carried out during the past two decades solidified the relatively new science of plasma physics. The understanding of small-amplitude wave propagation and of fluctuation phenomena achieved in the 1960s is a necessary prerequisite for many plasma applications.
- The 1970s saw the extensive development of coherent and turbulent nonlinear plasma physics, which is proving to be even more fundamental. The development and widespread use of advanced computational techniques provided an important link between theory and experiment.
- Direct support for basic laboratory plasma-physics research has practically vanished in the United States. The number of fundamental investigations of plasma behavior in research centers is small, and only a handful of universities receive support for basic research in plasma physics. A striking example is the minimal support for basic research in laboratory plasmas by the National Science Foundation.
- Because fundamental understanding of plasma properties precedes the discovery of new applications, and because basic plasma research can be expected to lead to exciting new discoveries, increased support for basic research in plasma physics is strongly recommended. The physics community should be encouraged to submit high-quality proposals for basic research in laboratory plasmas.
- A dedicated study of plasma physics can be expected to lead to important new research techniques and technological opportunities. For example, dense nonneutral plasmas composed mainly of high-energy electrons may become available with new types of accelerators, taking advantage of collective processes. In a related area, new types of particle accelerators using collective effects will contribute to

nuclear and high-energy physics, energy-related applications, and defense. New coherent radiation sources based on plasma technology, particularly x-ray lasers and generators of submillimeter microwaves, will have applications in materials research, medicine, defense, and no doubt in other areas not yet perceived.

- The impact of plasma physics on related sciences and on technology has continued to grow since the birth of modern plasma physics in the late 1950s and will continue to grow for the foreseeable future, provided a strong research base for plasma physics is maintained by an adequate level of support.

### **Fusion Plasma Confinement and Heating**

We divide the major findings and recommendations into those that pertain to magnetic confinement, in which strong externally applied magnetic fields are used to confine a high-temperature fusion plasma, and those that pertain to inertial confinement, in which a solid pellet is imploded to ultra-high densities.

### **MAGNETIC CONFINEMENT**

- In all the main approaches to the magnetic confinement of fusion plasmas, the principal measures of performance—plasma density, temperature, and confinement time—improved by more than an order of magnitude as a result of intensified fusion research in the 1970s. One approach—the tokamak—has already come within a modest factor of meeting the minimum plasma requirements for energy breakeven in deuterium-tritium plasmas. These achievements have been made possible by rapid advances in plasma science.

- The techniques used for plasma control and heating, the technology of high-power heating sources, and the precision of plasma measurements all improved dramatically during the past decade. There were equally rapid advances in plasma theory and numerical modeling, which are now able to explain much of the observed dynamical behavior of magnetically confined plasmas. The establishment of the National Magnetic Fusion Energy Computer Center (NMFECC) made many of these advances in theoretical modeling and data interpretation possible.

- A particular strength of the U.S. fusion program is its broad base, which includes research on several alternatives to the mainline confinement concepts, to ensure that the maximum potential of fusion is ultimately realized.

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- A new generation of magnetic fusion facilities, coming into operation worldwide, will, in the mid-1980s, extend experimental plasma parameters to reactorlike densities, temperatures, and confinement times.

- However, if the United States' preeminent position in the worldwide fusion program is to be maintained into the 1990s in the face of aggressive Japanese and European competition, the pace of new-device authorization that characterized the early 1970s will have to be restored soon.

- A vigorous base research program that emphasizes both increased scientific understanding and research on improved reactor concepts (advanced tokamaks, tandem mirrors, and other approaches) is essential. The purpose of concept improvement activities should be both to increase scientific understanding and to improve reactor prospects. Historically, the interplay between these two lines of effort has led to our most creative physical insights and concepts. Such a program is essential to technical progress and to the training of talented new people.

- The demonstration and experimental study of an ignited fusion plasma is the obvious next research frontier after attainment of scientific breakeven. Indeed, the achievement of fusion requires that this goal be attained. While the scientific understanding of many key plasma phenomena can best be gained on moderate-size experimental facilities, ultimately plasma-confinement properties must be investigated under conditions of intense alpha-particle heating, which will require an ignited plasma core. The fusion program is at the point where consideration of such experiments can proceed with some degree of realism. Obviously, ideas will continue to evolve rapidly as results from experiments, particularly the TFTR tokamak, become available in the next several years. In the near term, studies for a Burning Core Experiment should emphasize maximum scientific output with minimum project cost, consistent with the recent recommendations of the Magnetic Fusion Advisory Committee (MFAC).\*

- A vigorous research program is essential to technical progress in mainline tokamak and mirror research. Moderate-size experimental facilities are the primary sources of the scientific and technological innovations required to develop fusion to its fullest potential.

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\*Magnetic Fusion Advisory Committee Recommendations on the Tokamak Fusion Core Experiment, Department of Energy (July 1984).

- Continued research on alternative fusion concepts is essential to advance basic understanding of plasma confinement and to foster the development of approaches that show significant promise of improved reactor configurations.

- Intensive research must continue on the theoretical and computational descriptions of magnetically confined plasmas and on supporting experiments in basic plasma physics. These have been a source of many promising new concepts in fusion research.

- Continued strong university involvement will be essential to fusion research for the foreseeable future. Universities augment fusion research in the national laboratories in several unique and important ways. They educate and train professional fusion researchers, they provide the fusion program access to a breadth of talent and intellect in the sciences and engineering, and their research is a major source of innovative ideas and scientific and technological advances.

### INERTIAL CONFINEMENT

The United States has maintained world leadership in inertial-confinement fusion research since its inception in the late 1960s. Its near-term applications are military, with promising long-term applications to energy production. An inertial-confinement fusion reactor would have a relatively small containment volume, and its operation, maintenance, and repair may be relatively simple. An issue important to inertial-confinement fusion research is that classification limits access to technical information.

During the past decade, a vigorous international research effort was established to investigate the inertial-confinement approach to fusion. An impressive array of experimental facilities was developed, including neodymium-glass and CO<sub>2</sub> lasers and light-ion accelerators, which has resulted in considerable scientific progress. Investigations of laser-coupling physics over a wide range of intensity and wavelength showed that lasers with wavelengths of a micrometer and shorter have very good coupling. Deuterium-tritium fuel was heated to thermonuclear temperatures in laser-irradiated implosions. Shells were ablatively accelerated to speeds above 10<sup>7</sup> cm/s, with velocity nonuniformities of less than 5 percent. In implosions, final fuel densities of 100 times the liquid density of deuterium-tritium were achieved with fuel temperatures of about 5 million degrees. These fuel densities are within a factor of 10 of the compression needed for a high-gain target.



On the basis of the significant scientific and technological progress, we recommend the following near-term emphasis and strategy for inertial-confinement fusion research:

- Use present driver facilities to determine the physics and scaling of energy transport and fluid and plasma instabilities to regimes characteristic of high-gain targets.
- Use the new generation of drivers under construction to implode deuterium-tritium fuel mixtures to 1000 times liquid density required for high-gain targets and to implode scale models of high-gain targets to the density and temperature of the full-scale target.
- Identify and develop cost-effective, multimegajoule driver approaches.

Timely execution of this strategy will provide the basis for a decision in the late 1980s on the next generation of experimental facilities. Drivers in excess of a megajoule would allow demonstration of high-gain targets for both military and energy applications.

As a final point, research in inertial-confinement fusion is carried out primarily in the national laboratories, with smaller but prominent efforts at several university, industrial, and other research laboratories. In view of the importance of basic physical processes in inertial fusion, and the requirements for advanced technology development, there should be continued emphasis on maintaining and strengthening the breadth of institutional participation.

#### **Space and Astrophysical Plasmas**

- Many practical systems, both civilian and defense, must operate in the highly variable and potentially hostile plasma environment of the Earth and solar system. Plasma processes in this environment also influence and even disrupt important ground-based systems over local and regional scales.
- The solar system, including the Sun itself, is the primary laboratory in which astrophysical processes of great generality can be studied in situ; these processes include magnetic reconnection, plasma heating and particle acceleration, magnetohydrodynamic wave generation and propagation, magnetoconvection, magnetoturbulence and turbulent magnetic-field diffusion (including spatially intermittent magnetic fields), collisionless shock formation, wave-particle interactions, and the interaction of plasmas with radiation.
- Because of the wealth of pertinent information flowing from solar-system plasma physics, and continuing advances in large-scale

numerical modeling, magnetohydrodynamics and plasma physics are becoming essential to the interpretation of many astronomical observations.

- Studies of plasma behavior in extreme astrophysical environments, such as pulsars, enriches basic theory and may suggest future laboratory investigations.

- Cosmic-ray observations provide important information about space and astrophysical plasmas. The plasma physics of cosmic-ray acceleration and transport made especially rapid progress in the past decade. The improved precision of cosmic-ray composition measurements now makes possible quantitative tests of theories of nucleosynthesis and galactic chemical evolution.

- A vigorous program of observations, measurements, and experiments, in space and on the ground, is key to productive research in space and astrophysical plasma physics. We recommend implementation of the comprehensive research strategy outlined in the Space Science Board publication *Solar-System Space Physics in the 1980's: A Research Strategy* (National Academy of Sciences, Washington, D.C., 1980). These programs, including the International Solar Terrestrial Program, are the primary ones that will explicitly contribute to our knowledge of the physical processes in large-scale plasmas. We endorse the programs proposed in the Astronomy Survey Committee report *Astronomy and Astrophysics for the 1980's* (National Academy Press, Washington, D.C., 1982), because they will make significant contributions to many problems in plasma astrophysics.

- We recommend establishment of a national computational program dedicated to basic plasma physics, space physics, and astrophysics that will maintain the state of the art in the technology appropriate to large-scale theoretical models and simulations and provide access to users on the basis of peer review. The implementation of such a program should be studied forthwith by a committee drawn from the affected disciplines.

- In view of the increasing precision of its experimental and theoretical techniques, and in view of its wide applicability to space physics, astrophysics, and technology, we recommend that plasma physics become a regular part of the university science curriculum.

- In view of the many common processes underlying both laboratory and space plasmas, such as reconnection of magnetic field lines and particle acceleration by plasma waves, there should be an expanded effort to simulate space- and astrophysical-plasma processes in the laboratory.

### Fluid Physics

The diverse research field of fluid physics is vital to the country's economic health and defense because of its direct impacts on transportation and chemical and material processing systems and its central role in the understanding of many geophysical and astrophysical phenomena. We summarize here our findings and recommendations related to research support and education in fluid physics.

- Access to major computational and experimental research facilities in fluid physics is limited. The computer has emerged as a significant tool whose applications range from the rapid organization of data and its subsequent analysis and display to the direct numerical simulation of the major features of limited volumes of turbulent flow. In many applications of computational fluid dynamics, such as aircraft design, there is aggressive competition from Europe with indications of similar efforts in Japan. In addition, there are unique national experimental facilities that are unavailable for basic fluid-physics research.

- It is strongly recommended that unique national fluid-physics facilities, both computational and experimental, be made available to the university and nongovernment communities for basic research. Direct allocations of time and other resources will be necessary in order to maintain an appropriate balance between basic research and development and to assure steady operational funding of these facilities.

- Many of the recent advances in fluid-physics research have originated with new instrumentation techniques coupled with an increasing ability to analyze larger quantities of data, as for example in the study of turbulent flow.

- We recommend a concerted research effort to devise instrumentation for essentially simultaneous, time-resolved, multipoint measurements of flow properties throughout large volumes. The instruments might be based on laser holographic methods, on multiprojection (tomographic) techniques, or on a combination of these and other as yet unexplored methods. This will require the acquisition of major hardware components, as well as identification of sufficient resources for their development and deployment.

- The mathematical techniques that have been developed and refined during the past 15 years have become increasingly important tools in advancing fundamental understanding of complex flow and in

improving numerical methods, as well as in testing the results of numerical simulation.

- Given the increasing importance of numerical simulation techniques, we recommend that these techniques not be allowed to obscure the fundamental importance of analytical methods.

- Funding for basic research in fluid physics comes from a wide variety of sources, but the field lacks an individual national identity. Despite the common technical threads that bind fluid physics as a scientific discipline, its basic research support is poorly organized and lacks quantity, continuity, and the early recognition of significant new opportunities.

- We recommend that a continuing survey of research support in fluid physics be established and monitored by an appropriate agency. The information developed by this survey would help to coordinate research and would identify basic areas that offer significant new opportunities or are neglected because they are not included within the mission of a support agency. Areas that receive excessive overlapping support could also be identified.

- Education and university research in fluid physics is conducted primarily in engineering and applied mathematics departments in the United States. During 1983, there were more than 50 times as many fluid-dynamics-related Ph.D. theses in engineering departments as there were in physics departments. Physics research in the United States has been deprived thereby of the opportunity to participate in many fundamental and applied problems involving fluid physics.

- The use of fluid physics is pervasive in many areas of modern science and technology. We strongly recommend that physics departments consider requiring an undergraduate course in fluid physics. We similarly recommend that engineering schools consider a required upper-division undergraduate course in modern physics. These important steps would enhance collaboration between the physical and engineering sciences.

- The need for dedicated, separate funding for modern laboratory equipment in fluid mechanics is at least as severe as the well-publicized needs in other branches of physics. Fluid-flow instrumentation, especially optical, will continue its recent rapid progress. Unfortunately, as a result, university laboratory equipment will become even more out of date.

- We recommend that this deficiency in instrumentation be addressed in a timely manner.

## RECENT ACCOMPLISHMENTS AND FUTURE RESEARCH OPPORTUNITIES

In this section, we summarize selected significant research accomplishments during the past decade and future research opportunities in those areas reviewed by the Panel on the Physics of Plasmas and Fluids. Considerably more detail is given in subsequent chapters.

### General Plasma Physics

#### SIGNIFICANT RECENT ACCOMPLISHMENTS

Selected significant accomplishments in general plasma physics during the past decade include the following:

- Major advances in understanding the physics of nonlinear (i.e., large-amplitude) plasma phenomena. These include experimental, theoretical, and computational studies of large-amplitude plasma waves, including the trapping of particles in the potential troughs of these waves; the breaking of waves; and the passage toward turbulent behavior. Also included is the discovery of two different types of plasma solitons (Langmuir and ion-acoustic). Solitons are highly localized, self-perpetuating wave entities with remarkable properties of coherence. Other developments include the elucidation of the ponderomotive forces (radiation pressure) exerted by large-amplitude waves in plasmas, the understanding of "parametric" instabilities (two coexisting plasma waves amplifying a third wave), and the prediction and confirmation of radio-frequency driven dc currents in tokamak magnetic confinement devices.
- There have also been major advances in computer capabilities. These led to realistic computer simulation experiments that follow thousands of "particles" and model the collective behavior of real plasmas. Another important advance was the use of on-line computers to analyze, correlate, and immediately display synoptic data from the plasma diagnostics on laboratory experiments.
- Development of high-voltage, high-current accelerators that produce 10- to 20-million-megawatt pulses of power with applications to the generation of intense charged-particle beams and x-ray pulses.
- Development of highly collimated intense beams of energetic electrons, at the million-megawatt level, as in the Livermore Advanced Test Accelerator (ATA), and the study of beam propagation in vacuum and in low-pressure gases.

- Development of tunable, coherent "free-electron" radiation sources that generate intense monochromatic radiation at wavelengths ranging from centimeters to micrometers (microwaves, infrared and visible light). These sources include relativistic magnetrons, gyrotrons (cyclotron masers), and free-electron lasers.

- Major advances in atomic physics, including measurements of electron-ion ionization and recombination processes, understanding of radiation losses, interpretation of x-ray lines, and x-ray laser experiments. New spectroscopic diagnostics making use of magnetic dipole transitions and charge exchange were introduced into fusion research.

- Minimum energy states have been predicted for a class of plasma-field configurations, subject to the constraint of global helicity. The tendency for reversed-field pinch and spheromak configurations to relax toward these states has now been confirmed experimentally, allowing unique approaches to configuration sustainment and current drive. Understanding the basic physics of relaxation to a minimum energy state under the constant-helicity constraint may have a wide range of applications, e.g., to the magnetosphere as well as to magnetic fusion configurations.

#### FUTURE RESEARCH OPPORTUNITIES

Particularly promising research areas are summarized below:

- Development of new particle accelerators of two types: first, high-current accelerators that necessarily involve collective effects, that is, electric and magnetic fields generated by charged particles; second, accelerators employing the intense electromagnetic fields generated by high-power lasers to achieve ultrahigh particle energies.

- Further development of free-electron radiation sources, to produce tunable radiation sources, some of exceptionally high-power output. Applications include spectroscopy, condensed-matter research, isotope separation, communications and radar, and biology and medicine.

- Advances in understanding strongly coupled plasmas, i.e., dense ionized matter where coulombic correlations among particles determine bulk and dynamic properties. Such plasma states occur in inertial fusion targets, large planets, and red giant and neutron stars. The use of large computers and novel computer simulation techniques is expected to lead to major developments in this important field, which is central to the understanding of matter at ultrahigh densities.

- Developments in the physics of nonneutral plasmas. A nonneutral plasma is composed mainly of one species of charge (i.e., electrons or ions). For example, a pure electron plasma confined by external electric and magnetic fields has many unique properties, including great stability. Indeed, confinement times of hours have been observed for such plasmas. Theoretical predictions indicate that nonneutral plasmas can be cooled to the point that the electrons enter a liquid or even a crystalline state.

- Advances in the understanding of the excitation, ionization, and recombination of multiple ionized atoms. Quantitative plasma spectroscopy is needed to test the validity of the atomic data base and reaction kinetics, as are more precise wavelengths. Self-consistent calculations of radiative and transport properties of dense and hot matter continue to pose difficult challenges to many-body theory.

- Further advances in computers and their use in plasma simulation to the point where realistic three-dimensional plasma simulations can be envisaged.

### **Fusion Plasma Confinement and Heating**

#### **SIGNIFICANT RECENT ACCOMPLISHMENTS— MAGNETIC CONFINEMENT**

The last decade saw greater progress than any previous decade in fusion's history. Many of the most significant accomplishments were achieved within the U.S. magnetic fusion program. Among these are the following:

- In the tokamak approach, the achievement of well-confined plasmas at 80-million-degree ion temperatures, approaching those needed for fusion. Before these results were obtained, the theory of microinstabilities in tokamaks had predicted that, at such temperatures, new forms of fine-scale turbulence might arise, associated with the entry of the ions into a previously unexplored low-collisionality regime. Although enhanced fluctuations were indeed observed in the experiments, energy transport was not affected significantly. These results have led to a re-evaluation of, and fundamental improvements in, the theory of anomalous transport due to microinstabilities in tokamaks.

- Also in the tokamak, the demonstration of energy confinement of dense plasma (at a lower but significant temperature) for values of the Lawson  $n\tau_E$  parameter almost equal to those needed in a full-scale

fusion reactor, and the identification of empirical energy-confinement scalings that are favorable for reactor sizing. According to one empirical scaling, which fits the data from ohmically heated tokamaks over a wide range of parameters, the confinement time varies with the cube of a plasma linear dimension, as would be expected for a diffusive process in which the transport coefficient depends on gradient-induced anomalous processes.

- The successful use, in accordance with theoretical prescriptions, of radio-frequency waves to drive plasma currents in tokamaks, thereby permitting confining magnetic fields to be steady state, a property of importance to the practicality of tokamak reactors. Experiments on radio-frequency current drive have exhibited a hot-electron population of current carriers in agreement with theory and have verified the predicted dependence of current-drive efficiency on plasma density.

- The achievement of beta values (ratio of plasma pressure to magnetic pressure) in tokamak plasmas approaching those required for an economic reactor.

- In the mirror—the principal alternative U.S. approach to magnetic fusion—the progressive elimination of high-frequency instabilities that had been an obstacle to progress. It has been the development of a detailed theoretical understanding of the dependence of these high-frequency instabilities on the velocity distribution of mirror-confined ions that has led to their suppression by a variety of techniques in present-day experiments and to their predicted elimination in a thermal-barrier tandem mirror.

- The introduction of the tandem-mirror concept and the demonstration that tandem mirrors can effectively suppress plasma leakage through the ends, thereby pointing the way toward mirror systems adequate for fusion applications. A tandem-mirror reactor would have mirror end cells and an axial thermal-barrier potential profile to suppress end losses from a large-volume, high-beta, ignited central-cell plasma.

- The development and application of multimegawatt neutral-beam sources that can heat both mirror and tokamak plasmas to fusion temperatures. Neutral-beam heating experiments have verified that beam ions deposit their energy in tokamak and mirror plasmas by means of well-understood classical processes.

- Major advances in plasma theory and computation, which are now able to describe in detail most large-scale phenomena of confined



ization to date, the development of a broader experimental data base, accompanied by advances in the theoretical description of large- and fine-scale turbulence in tokamaks, is almost certain to lead eventually to a sound fundamental understanding of these processes.

- Confirmation of tokamak scaling laws by means of the simultaneous achievement of fusion temperatures, densities, and confinement times, early in the second half of the 1980s as the new facilities now coming into operation are brought up to full performance.

- Optimization of the plasma beta (plasma pressure relative to magnetic pressure) in tokamaks, to approach the limit predicted by theory (about 10 percent). Optimization of the tandem mirror so as to achieve the projected beta values of about 40 percent. Achievement of these beta values will require sound guidance from theory and computation as to the detailed magnetic designs and the plasma profiles and shapes that provide the greatest protection against various types of gross plasma instability.

- Detailed understanding of the physics of self-generated electric potentials within plasmas, essential to the operation of tandem-mirror systems. This will require well-diagnosed experiments on tandem mirrors, aimed at determining the relationship between the axial potential profile and the power applied to heating the electrons in the thermal-barrier region.

- Scale-up of the most promising alternative magnetic-confinement concepts to experimental facilities capable of achieving reactorlike plasma parameters. This will require: (i) the scale-up of reversed field-pinch experiments to test sustainment of, and confinement in, stable high-beta configurations at higher plasma temperature, (ii) the improvement of formation techniques and the determination of energy-confinement scaling as temperatures are increased beyond the present 100-electron-volt range into the collisionless regime in compact toroids, and (iii) the demonstration of stability and favorable confinement at moderate beta values in stellarators at low plasma collisionality. All of these advances depend critically on improved understanding of the dynamics of confined plasmas.

- Increased fundamental understanding of hot plasmas made possible by, and contributing to, these advances in fusion research. This will require well-diagnosed experiments on the major facilities, a vigorous program in plasma theory and computer simulation, and carefully designed small-scale experiments that can be devoted exclusively to detailed studies of fundamental plasma processes.

**SIGNIFICANT RECENT ACCOMPLISHMENTS—  
INERTIAL CONFINEMENT**

Scientific advances in inertial fusion research were made by elucidating basic physics, by conceptual breakthroughs, and by the development of advanced technologies. They include the following:

- Advances in pellet design, which have high leverage, since they can raise potential pellet gains, increase efficiency, and thereby reduce driver and system requirements (and cost). For example, the idea of using tailored laser pulses to increase gain and reduce the required driver energy gave inertial confinement research its initial impetus. The x-ray hohlraum approach to implode pellets may significantly reduce the beam illumination uniformity requirements.

- Driver technology advanced steadily during the past decade. Lasers progressed from the 10-joule range to present-day drivers (NOVA, ANTARES, and PBFA II) with outputs of many tens of kilojoules. Megajoule-class drivers, needed for reactors, are now within technological reach.

- Light-ion driver technology progressed rapidly; highly efficient ion diodes were developed; ion beams were transported more than 1 meter from these diodes and focused to more than 1 terawatt per square centimeter. Recent developments in ultra-fast plasma-erosion switches are likely to lead to a new generation of high-power electron and light-ion accelerators.

- The laser-target coupling processes were identified at 1- and 10- $\mu\text{m}$  laser wavelengths. Although there are still many gaps, the understanding gained thus far favors the shorter laser wavelengths, where more efficient laser-plasma coupling was demonstrated.

- Cold targets were accelerated to speeds above 100 kilometers per second with nonuniformities below 3 percent, close to the conditions required for high-gain inertial fusion. Pellet shells must be uniformly imploded at high speeds and yet remain cold to compress the fuel properly.

- Deuterium-tritium fuel in laser-irradiated pellets was heated to thermonuclear temperatures early in inertial fusion research. More recently, ablatively imploded pellets compressed fuel to very high density (100 times solid density). Simultaneous fuel heating and high-density compression are needed for significant energy yields.

- There have been major advances in the development of the scientific tools needed to understand the physics of the high-energy-density and short-time-regime characteristic of inertial fusion. Espe-

cially noteworthy were advances in experimental diagnostics and computer modeling.

- Parametric instabilities of the laser radiation in strongly inhomogeneous plasmas, causing Raman and Brillouin scattering and conversion to plasma and ion waves, were predicted by theory, confirmed by experiment, and shown to be important processes affecting laser-plasma coupling.

#### FUTURE RESEARCH OPPORTUNITIES— INERTIAL CONFINEMENT

Many scientific and technological issues will be addressed with the hundred-kilojoule drivers that will be available in the mid-1980s, while others await megajoule systems. Future research opportunities in inertial fusion include the following:

- Detailed tests of the improved laser-plasma coupling with short-wavelength light will be made. It is especially important that this information be obtained under plasma coronal conditions modeling those in a reactor.

- Experiments defining the hydrodynamic stability of accelerated targets and imploding pellets will provide information essential to high-gain pellet design, which will continue to have high leverage and will, in large part, define future technological requirements.

- There are several approaches to making the deposition of driver-beam energy on the pellet acceptably uniform. One promising approach, converting the beam energy to x rays in a hohlraum, which in turn drives the implosion, will be tested experimentally in detail.

- Several innovative ways of making laser beams much more uniform, such as the induced spatial incoherence technique and precision beam control, will be tested in large systems. Highly symmetric beam illuminations would allow beam energy to be used directly for pellet implosion.

- Driver technology will continue to advance toward a high-energy, high-repetition-rate, efficient driver suitable for energy applications. One promising system under development is the krypton-fluoride excimer laser; megajoule-class glass-laser designs are also being evaluated. Heavy- and light-ion beam drivers offer high potential efficiency and repetition rates.

- There will be opportunities to study the properties of hot matter at densities 100-1000 times solid densities.

### Space and Astrophysical Plasmas

#### SIGNIFICANT RECENT ACCOMPLISHMENTS

Selected significant accomplishments in space and astrophysical plasma physics are summarized below:

- The first spacecraft studies of the magnetospheres of Mercury, Venus, Jupiter, and Saturn occurred during the past decade. The concepts used to understand the Earth's magnetosphere were successfully extended to these magnetospheres, and significant new physical phenomena were discovered. The generality of the concept of a magnetosphere in solar-system and astrophysical environments was recognized.
- Rigorous models of magnetic-mirror confinement, radial diffusion, and turbulent pitch-angle scattering of energetic ions and electrons were created and successfully tested by observations in the magnetospheres of Earth, Jupiter, and Saturn.
- Rigorous analytical theory and numerical simulation established the correct magnetohydrodynamical description of reconnection—the conversion of configurational magnetic energy to plasma kinetic and thermal energy. Theoretical understanding of the more fundamental collisionless description was consolidated. Experimental evidence for reconnection was provided by laboratory measurements and by observations in the Earth's magnetosphere.
- A coherent program of active and passive radar experiments, chemical releases, rocket measurements, analytical theory, and numerical simulations devoted to the equatorial ionosphere led to the most complete analysis of the nonlinear development of the Rayleigh-Taylor instability in plasma physics.
- Detailed observations of the solar surface have forced a re-evaluation of our current theoretical understanding of hydrodynamic and magnetohydrodynamic flows: in consequence, sophisticated analytical and numerical models that aim to describe the observed highly intermittent magnetic fields on the solar surface have been initiated.
- The detection by the Einstein Observatory spacecraft of stellar coronal x rays proved that solarlike magnetohydrodynamic and plasma processes are central to the physics of the atmospheres of all stars that have convecting outer layers.
- A clear understanding of electron heat transport in the solar wind was achieved by systematic measurements of superthermal electrons. Quantitative studies of the conduction of heat between the solar corona

and chromosphere, which promise to make interpretation of chromospheric and transition-region line emissions more secure, were initiated.

- Synoptic measurements of the dependence of the Earth's bow-shock structure on the properties of the upstream solar wind substantially increased the basic understanding of collisionless shocks.

- Measurements of the energetic particles and plasma turbulence associated with interplanetary shocks and planetary bow shocks began to be used to test self-consistent shock acceleration theories. These results are providing a solid basis for theories of the acceleration of cosmic rays by supernova shocks.

- Measurements of the isotopic composition and elemental abundances of cosmic rays defined the lifetime of cosmic rays in the galaxy and suggested that they are accelerated directly out of the interstellar medium after being produced by the stellar nuclear-burning cycle.

- Detection of an x-ray line, plausibly at the electron cyclotron frequency, provided the first experimental indication that neutron stars have superstrong magnetic fields, of order  $10^{12}$  gauss—a fundamental hypothesis of pulsar and galactic x-ray source theories.

- Energetic plasma jets were found to occur in a wide range of astronomical objects, from compact stars to active galaxies and quasars.

- Plasma theory, numerical simulation, and laboratory experiments provided a basic explanation of the Alfvén critical flow velocity criterion for the rapid ionization of the neutrals in a plasma-neutral gas mixture.

#### FUTURE RESEARCH OPPORTUNITIES

During the next decade, the expected research opportunities and accomplishments include the following:

- The first stage in the exploration of solar-system plasmas, including planetary magnetospheres and the large-scale heliosphere, will be nearly completed by the *Voyager* encounters with Uranus and Neptune, by the *Galileo* mission to Jupiter, and by the *International Solar-Polar Missions* to high heliographic latitudes. The most important remaining exploratory objective will be in situ measurements of the solar corona.

- The plasma environment of the Earth will be subjected to controlled study, and, perhaps, to a measure of control, through the

systematic use of active experiments and by synoptic observations made by the International Solar-Terrestrial Physics Program.

- High-spatial-resolution observations in the optical region by the Solar Optical Telescope; in the radio region by the VLA, VLBI, and the planned VLBA; and in the UV and x-ray regions by other planned space experiments, such as the Advanced Solar Observatory, will provide essential information for defining quantitative models of solar-surface convection, surface magnetic fields and dynamics, solar flares, and coronal heating, thereby creating the basis for general understanding of stellar activity.

- The growing ability to make a series of detailed high-resolution observations in many wavelength ranges (such as in the x-ray range by the Advanced X-Ray Astrophysics Facility) will render many astrophysical objects increasingly subject to theoretical models that explicitly take plasma processes into account.

- Understanding of many space-plasma processes will be sufficiently quantitative to make them reliable components of models of large-scale space and astrophysical systems.

- The first generation of large-scale numerical models of space and astrophysical systems will be completed. Such models will likely make plasma physics central to the interpretation of many astronomical observations and motivate new and different kinds of observations.

### **Fluid Physics**

#### **SIGNIFICANT RECENT ACCOMPLISHMENTS**

During the past decade, significant research accomplishments in fluid physics included the following:

- The revolutionary development of computational fluid dynamics, which has made possible the solution of problems that previously defied theoretical analysis and experimental simulation, such as convection and circulation within the Sun and planetary atmospheres, and the nonequilibrium flow surrounding the Space Shuttle on re-entry. The time and expense required to design aircraft wings, internal combustion engines, nuclear fusion and fission devices, and surface and undersea naval vehicle components were reduced. Computational fluid dynamics has increased the understanding of flows in the presence of combustion, chemical reactions, and multiple phases.

- An improved basic understanding and ability to model and compute turbulent flows. These improvements include basic insight into

how mechanical systems display chaotic behavior; a better appreciation of the role, organization, and interaction of fluid structures of all sizes; new diagnostics and methods of interpreting data; and the use of large-scale computing.

- Single and multiphoton excitation, as well as scattering techniques, were developed to study the energy budgets of severe gas-dynamic environments such as flames, permitting the first detailed investigations of complicated chemically reacting flows.

- Large-scale turbulent and coherent fluid-dynamic structures were identified in the Earth's oceans and atmosphere and the atmospheres of Jupiter, Saturn, and Venus. Their successful simulation using eddy-resolving computer models gives a new view of laboratory turbulence and the general circulation, storms, and weather of the atmosphere and deep ocean.

- Fluid-dynamic modeling led to basic new knowledge of our cardiovascular, reproductive, and urinary systems and many other internal organs of the human body. It has also illuminated the locomotion of biological organisms, from a single ciliate cell to the hummingbird and the tuna. Fluid-dynamic principles proved vital to the design of artificial organs, cardiovascular implants, prostheses, and the development of new clinical diagnostic methods.

- Important advances were made in understanding the collective behavior of dilute particulate and aerosol suspensions. New mathematical methods were devised for treating large-amplitude droplet deformation and the strong interaction between three or more particles, which have potential application to denser systems. These advances have led to new insight into the behavior of clouds, fluid separation phenomena, geological magma chambers, climate dynamics, and fluids with complex rheologies, such as blood.

- The central unifying idea of modern geology is the fluid-convection interpretation of the motion of the Earth's upper mantle. The implications for planetary evolution, earthquakes, vulcanism, and mineral and petrochemical resource exploration were made clear in the last decade.

- Dimensional analysis and recent theoretical understanding of jet noise, acoustic damping, and turbulent flows led to a thousandfold reduction in the energy of acoustic emissions from aircraft, resulting in major reductions in perceived noise levels.

- An accelerated pace of accomplishment in understanding high-speed flows has been made possible by improved analytical tools, numerical simulation, and new experimental techniques. These technical advances inspired significant improvements in the efficiency of

commercial transport, in the effectiveness of high-performance aircraft, and in manned re-entry from space.

- Simple wavelike connections were discovered in terrestrial climate studies. Circulation changes, like El Niño of the tropical Pacific, are communicated across the globe and have large effects on rainfall and winds.

- Noninvasive instrumentation techniques, such as those that detect blood-flow-initiated acoustic emissions from the human body, or neutrally buoyant probes that track, via satellite, the transient and mean circulation of the oceans, significantly advance the understanding of many fluid-flow phenomena.

- New constitutive models based on molecular physical structure led to a better understanding of the striking flow properties of non-Newtonian fluids, such as polymer solutions and drag-reducing agents.

- The synergistic interaction of chemical, fluid, and optical physics has resulted in the new continuous high-power laser. This success led to the identification of fluid phenomena important to the performance of electric discharge and other gas-media lasers.

- The development of numerical simulation techniques has permitted the study of molecular motion in transition-regime gas flows, which occur between the limits of collision-dominated continuum flow and collisionless, free-molecular motion.

#### FUTURE RESEARCH OPPORTUNITIES

During the next decade, the expected research opportunities and accomplishments in fluid physics include the following:

- Rapid advancement in the basic understanding of the characteristics and origins of turbulence, including investigations of the connection between the routes to chaos found for systems with a finite number of degrees of freedom and the continuous instability that is fluid-dynamic turbulence.

- Improvements in the ability to control turbulent flows will lead to novel drag and noise-reduction techniques; increased combustion efficiency; and control of separation, spreading, and mixing. Major advances in technology will result from the ability to predict flow with turbulent zones.

- Continued rapid development of advanced computational techniques in fluid dynamics, together with the next generation of computers, will provide the opportunity to calculate and obtain a new level of physical understanding of complex three-dimensional compressible



viscous flows. It will then be possible to optimize more effectively the design of high-performance aircraft, improve the forecasting of severe storm formation, attempt to predict global seasonal and annual climate changes, and realistically simulate and model planetary and astrophysical fluid-dynamical behavior.

- Development of powerful laser-based optical techniques for the rapid, multipoint measurement of flow-field properties, in conjunction with numerical techniques, will provide new types of information and increase the usefulness of large experimental facilities.

- In many technologically important fluid machines the flow is either separated or unsteady or both. With the help of modern instrumentation and computerized data analysis, we are beginning to understand the physics of such flows and how, often in combination, they can be used to improve technological devices ranging from heart valves to aircraft. These possibilities will present a major research challenge in the coming decade.

- The subjects of combustion and reacting flows are likely to yield new applications in the near future. Control of soot and other pollutants will result from the understanding of their production mechanisms. Basic studies of the interaction between chemical kinetics and fluid instabilities will result in an understanding of deflagration and the transition to detonation. Applications range from improved fuel economy to fire safety.

- We expect to see major advances in the understanding of multiphase flow systems, including the macroscopic and microscopic interface phenomena of interest in both industrial and geological processes, for example, the stability of the liquid-liquid interface leading to fingering in oil recovery, convective processes in the ocean, and the formation of layered structures in magma chambers.

- There will be increased interest in denser particulate systems, from the multiparticle interaction of finite clouds of particles to, more generally, the flow through porous media and filters based on the hydrodynamic interaction with their microstructure.

- Interdisciplinary study of basic cellular level biofluid dynamic processes in the presence of molecular forces will expedite explanations of such diverse phenomena as electrokinetic behavior in pores and membranes, the microstructure of osmosis, cell division, cellular transport function, gel hydration, and fluid motion in the intracellular tissue matrix. This will lead to a better understanding of basic cellular physiological function.

- Increased computational and data-handling capability will permit assimilation and understanding of the massive data sets required to

describe complex natural flow phenomena. For example, global-scale investigation of the oceans and climate dynamics is now possible using satellites and shipborne instruments. Using Lagrangian mathematical techniques and instruments that move with the fluid, we anticipate new views of turbulent dispersion; of the interaction between waves, turbulence, and mean flow in boundary layers; and in ocean-atmosphere circulations.

- The development of Monte Carlo computational techniques, which account for molecular motion in gas flows, will be extended to higher-density flows, permitting meaningful modeling of highly nonequilibrium, chemically reacting flow systems.

### **FUNDING AND MANPOWER RESOURCES**

The present funding levels for the areas of research described in Chapters 2-5 are summarized in Table 1.1, including a breakdown by government agency.

The funding level in Table 1.1 corresponds to a total of approximately 8600 professional researchers, assuming an average expenditure of approximately \$150,000 per researcher. The incremental funding and manpower required to carry out the recommended research programs over the next 5 years are delineated in subsequent chapters. Specific areas in which there is a critical manpower shortage are also identified (e.g., coherent radiation generation, atomic physics, basic experimental plasma physics, computational plasma physics and fluid dynamics, and plasma astrophysics).

### **INSTITUTIONAL INVOLVEMENT**

The subjects of plasma-physics and fluid-physics research cover an extremely wide range of interests and applications, from basic astrophysics to such applications as fusion energy and long-range weather prediction. Correspondingly, the institutional structure within which the studies are carried out spans the entire range of research institutions—from academe to industry. In what follows, we give a brief description of the institutional makeup of the subfields covered in this report.

#### **General Plasma Physics**

The funding for general plasma physics comes almost exclusively from government agencies, with major contributions from defense-

TABLE 1.1 Fiscal Year 1984 Funding Summary (in \$ Millions)

	DOE	NSF	DOD	NASA	NOAA	Total
General plasma physics	2.5	3.4	67.6	—	—	73.5 <sup>a</sup>
Fusion plasma confinement and heating						
(a) Magnetic	471	—	—	—	—	471 <sup>b</sup>
(b) Inertial	170	—	—	—	—	170 <sup>c</sup>
Space and astrophysical plasmas	2	30	5	100	2	139 <sup>d</sup>
Fluid physics	25	80 <sup>e</sup>	170	110	42	427 <sup>f</sup>

<sup>a</sup> DOD funding total includes: \$4 million, ONR; \$36 million, DARPA; \$6 million, AFOSR; \$1.6 million, ASD (Wright-Patterson); and \$20 million funding of the Naval Research Laboratory Plasma Physics Division. The \$36 million DARPA total includes \$10.5 million for operation of the ATA facility at LLNL. The \$2.5 million DOE total is for the Division of Advanced Energy Projects.

<sup>b</sup> Includes \$88 million for fusion development and technology, \$98 million for operation and modification of the TFTR tokamak facility, and \$55 million for construction (and supporting R&D) of the MFTF-B tandem mirror. The FY 1985 funding for magnetic fusion is \$437 million.

<sup>c</sup> Includes \$85.1 million for glass-laser, \$46.9 million for gas-laser, \$23 million for pulse-power research programs, and \$1.8 million for university research; it also includes \$12.9 million for construction of the PBFA-II light-ion facility. The FY 1985 funding for inertial fusion is \$169 million.

<sup>d</sup> This total does not include launch vehicles and tracking of space vehicles; it is an estimate of the funding for satellite plasma instrumentation and associated data analysis, theory, and numerical simulation.

<sup>e</sup> This total includes \$5 million for basic fluids research related to engineering support. The remaining is for atmospheric sciences and oceanography.

<sup>f</sup> These are estimates of FY 1983 funding. Includes \$230 million for national facility operation and research field measurements; it does *not* include the substantial funding used for the development testing of flight articles.

related agencies. The National Science Foundation provides only a small fraction of the support for this research area.

Most of the applied research in general plasma physics is performed at government laboratories, such as the Naval Research Laboratory, at national laboratories, or at industrial laboratories. A small portion of the research (approximately 15 percent) is performed at universities. The university effort, however, contains a major part of the innovative and basic components of the research.

### Plasma Confinement and Heating

Since plasma fusion research is a long-range, energy-related topic, its support (except for relatively small industrial components) derives

entirely from the Department of Energy (DOE). Correspondingly, the major part of magnetic confinement research is carried out at national laboratories (Livermore, Los Alamos, and Oak Ridge), at the Plasma Physics Laboratory at Princeton University, and at the GA Technologies industrial laboratory. Although representing a smaller fraction of the effort (approximately 10 percent), the universities represent a very important component, providing not only innovative ideas and major technical advances but also manpower training. Prominent among the universities involved in magnetic-confinement research are Columbia University, the Massachusetts Institute of Technology, New York University, the University of California at Los Angeles, the University of California at Berkeley, the University of Maryland, the University of Texas at Austin, and the University of Wisconsin. The *Magnetic Fusion Advisory Committee Report on the Long-Term Role of Universities in the Fusion Program*, Department of Energy (August 1983) provides a detailed delineation of the university involvement (approximately 26 institutions) in magnetic fusion research.

Similarly, the major part of inertial confinement research is carried out at national laboratories (Livermore, Los Alamos, and Sandia), at the Naval Research Laboratory, and at the KMS Fusion industrial laboratory. There is also a major research effort in inertial confinement fusion at the University of Rochester, with smaller but prominent research activities at Cornell University, the University of Arizona, the University of California at Davis, the University of California at Los Angeles, and the University of Maryland.

The present pre-eminence of U.S. research in magnetic-confinement fusion and inertial-confinement fusion is evidence favoring the present mix of institutions involved. However, as fusion comes closer to its goal of energy applications, the involvement of industry, currently largely limited (except for GA Technologies, TRW Systems, and KMS Fusion) to a technological support role, would be expected to increase. A strong industrial participation in fusion research and development is essential to eventual commercialization of fusion and spinoff applications.

#### **Space and Astrophysical Plasmas**

Support for space and astrophysical plasma research comes almost exclusively from three government agencies, The National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the Department of Defense (DOD), with some DOE and small industrial components. The research itself is performed at

various government and national laboratories, at a few industrial laboratories, and at many universities. A large fraction of the scientists engaged in this research are university based, yet much of the research is performed using the facilities of national and government laboratories, a circumstance that can be understood in terms of the obvious, necessary involvement of NASA. Although this division of effort has thus far been successful, especially when viewed in the light of the many recent accomplishments in space and astrophysical plasma research, the decreasing frequency of flight opportunities presents serious problems for university research, a situation that now requires urgent attention. A more consistent policy of support for university participation in space science is needed.

### **Fluid Physics**

Fluid physics, consistent with the unusual breadth of its applications (aeronautics, weather, and oceanography, for example), derives its support from a variety of agencies, notably NSF, NASA, the Air Force Office of Scientific Research, the Office of Naval Research, the National Oceanic and Atmospheric Administration (NOAA), and DOE. Major funding is received by institutions such as the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, and the NOAA atmospheric-science activity at Princeton University (weather prediction), which in turn supports field studies and other related activities. Universities are involved, at lower support levels, in a wide range of activities ranging from fluid-related biological research to aerodynamics to advanced gas-laser research. Fluid-physics research is at the forefront of many current problems in applied physics. Thus its institutional composition is very broad.

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## Fluid Physics

### INTRODUCTION AND OVERVIEW

Study of the physics of fluid motions or, in the present context, fluid physics, is among the oldest branches of the physical sciences.\* Despite this seniority, it continues to fascinate its practitioners with an eclectic collection of elegant problems. Our need to understand the world of flow around us, encompassing the nature of transport across biological membranes to the appearance of solitary waves in planetary atmospheres, remains a constant stimulation and adventure.

Fluid motion, which can exhibit the randomness of turbulent flow as well as much larger-scale coherent structures, provides one of the premier testing grounds for new developments in nonlinear dynamics. We are all affected by wavelike fluid-mechanic teleconnections that transmit information about the Earth's tropical oceans over vast distances to alter patterns of global atmospheric circulation. Swimming creatures, governed by the laws of efficient underwater travel, provide insights into the evolutionary pathways stimulated by changing environments or vacant biological niches.

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\*This review of fluid physics is restricted to areas where fluid motions are of dominant importance and have only included developments in the understanding of the properties and statistical mechanics of liquids and gases that are directly related to fluids in motion.

In common with many other branches of physics, fluid physics also finds a driving force in the existence of important problems in engineering. The pacing element for advances in many applications such as the efficiency of flight, the effectiveness of heat engines, and the productivity of chemical-processing systems is our understanding of the fundamentals of fluid motion. There are striking examples in the machines of engineering as they exist today, compared with history, that measure the magnitude of advances in our understanding of fluid physics. As it is beyond the scope of this report to catalog all of these advances, only a few will be mentioned as examples.

The modern transport plane, with swept wings and quiet engines, is a reflection of the progress in the last few decades of our understanding of high-speed flows. These configurations have been derived by a combination of originally empirical and more recently theoretical and conceptual constructs, made possible by advances in our understanding of the physics of flow. The gas turbine engine of today, although superficially similar to its historical counterpart, includes major improvements made possible by extensive efforts in fluid physics. Our increased knowledge of combustion and heat transfer, which were bought with so much difficulty through research, have led to lower exhaust pollution and longer life of the critical engine components. Many of today's chemical engineering plants have a throughput and an efficiency increased severalfold over those of only a decade ago, brought about by careful analysis of fluid mixing and heat transfer. These examples illustrate that basic knowledge in fluid physics moves quickly from research in flow physics to application because of the intense competitiveness of today's technological society.

In the following sections of this report we review significant recent developments as well as indicate where the next decade will provide compelling advances in our understanding. There is little doubt that these advances in understanding will in turn be matched almost immediately by innovations in technology.

We have also attempted to gain a useful measure of the scope and level of effort that marks this field by a review of those agencies of the government that support fluid-physics research. However, such a review cannot be exhaustive in the sense that the definitions of fluid-physics research tend to vary significantly with the nature and mission of the funding organization, nor are we able, in the time available, to explore private industry under whose sponsorship valuable contributions to the field have often been made. Nonetheless, these studies proved useful to the panel in its efforts to develop a series of findings with recommendations to both the funding and academic

communities, which we hope will enable us successfully to support and extend this important field of physics.

In the concluding section, we found it useful to subdivide fluid physics into branches distinguished by common phenomena. While these are certainly not unique, they do offer a convenience when one is attempting to obtain a feeling for the diverse activities in the field. There are also topical subject areas that are of current and future interest but that are not clearly highlighted by subdivision into phenomena-related branches. As a result, selected subject or discipline areas are also highlighted when they convey more clearly the main directions in research that rely on many phenomena. Finally, there are basic technical tools that are of fundamental importance to the advancement of fluid-physics research. Their status and expected development are outlined.

In summary, fluid physics remains intellectually stimulating because of the natural occurrence and importance of its problems. In addition, new levels of understanding of complex phenomena have further vitalized this field. Much of this understanding has been created by the development of powerful new tools that enable us to attack the nature of complex phenomena that hitherto have appeared to be intractable mysteries. Thus, the study of turbulence, complex high-speed flows, biological flows, and geological phenomena has been paced by new developments in powerful computational and instrumentation techniques. We look forward to the next decade as a time of excitement, adventure, and discovery. The associated implications for the mastery of many important practical problems so necessary to the well-being of our nation and the world serve as a further stimulus.

### **SIGNIFICANT ACCOMPLISHMENTS AND OPPORTUNITIES IN FLUID PHYSICS**

#### **Significant Recent Accomplishments**

- The revolutionary development of computational fluid dynamics has been used to solve problems that have previously defied theoretical analysis and experimental simulation, such as convection and circulation within the Sun and planetary atmospheres and the nonequilibrium flow surrounding the Space Shuttle orbiter on re-entry. In conjunction with improved performance, time and costs have been reduced in the design of aircraft wings, internal combustion engines, nuclear fusion and fission devices, and surface and undersea naval vehicle components. In addition, computational fluid dynamics has increased our



understanding of combustion, chemically reacting, and multiphase flows.

- The pace of accomplishment in high-speed flows has been accelerated by analytical methods, numerical simulation, and new experimental techniques. Inspired by these developments as well as by pressing social needs, significant advances have been made in the efficiency of commercial transport, manned re-entry from space, and the effectiveness of high-performance aircraft.

- Recent developments have led to exciting improvements in our understanding of turbulent flows. This has enhanced our ability to compute turbulent-flow characteristics and has provided new insight into how mechanical systems can display chaotic behavior. This understanding is being brought about by new measurement techniques combined with the availability of new powerful computational tools.

- Dimensional reasoning and recent theoretical understanding of jet noise, acoustic damping, and turbulent flows have led to a thousand-fold reduction in the energy of acoustic emissions from aircraft leading to major reductions in perceived noise level near airports.

- Important advances have been made in our understanding of the collective behavior of dilute particulate and aerosol suspensions. New solution methods have been devised for treating large-amplitude droplet deformation and the strong interaction between three or more particles with potential application to more dense systems. This progress has led to new insight into the behavior of clouds, fluid separation phenomena, geological magma chambers, climate dynamics, and complex rheological fluids such as blood.

- The central unifying idea of modern geology is the fluid-convection interpretation of the motion of the Earth's upper mantle. Important implications have been demonstrated for planetary evolution, earthquakes, vulcanism, and mineral and petrochemical resources.

- Large-scale turbulent and coherent fluid-dynamic structures have been identified in the Earth's oceans and atmosphere and the atmospheres of Jupiter and Venus. Their successful simulation using eddy-resolving computer models gives us a new view of laboratory turbulence and the general circulation, storms, and weather of the atmosphere and deep ocean.

- Simple wavelike connections have been discovered in terrestrial climate studies. Circulation changes like El Niño of the tropical Pacific are communicated great distances across the globe with massive effect on rainfall and winds.

- Single-photon and multiphoton excitation as well as scattering techniques have been developed to study the energy budgets of severe

gas-dynamic environments such as flames, permitting us for the first time to see inside complicated chemically reacting flows.

- Noninvasive instrumentation techniques that detect blood-flow-initiated acoustic emissions from the human body, or neutrally buoyant probes that track, via satellite, the transient and mean circulation of the oceans, represent important achievements that have promoted understanding of fluid-flow phenomena.

- Fluid-dynamic modeling has led to basic new knowledge of our cardiovascular, reproductive, and urinary systems as well as many of the internal organs of our bodies and the locomotion of biological organisms from a single-ciliate cell to the hummingbird and the tuna. Fluid-dynamic principles have been vital to the design of artificial organs, cardiovascular implants, prostheses, and the development of new clinical diagnostic methods.

- New constitutive models based on molecular physical structure have led to a better understanding of the striking flow properties of non-Newtonian fluids such as polymer solutions and drag-reducing agents.

- The synergistic interaction of chemical, fluid, and optical physics has created the new continuous high-power laser. The success of this example has led to the identification of the importance of fluid phenomena in the performance of electric discharge and other gas-media lasers as well.

#### **Significant Research Opportunities**

- Rapid advancement will continue in our understanding of the characteristics and origins of turbulence, including investigations of the connection between the routes to chaos found for systems with a finite number of degrees of freedom and the continuous instability that is fluid dynamic turbulence.

- As a result of the accelerating pace of physical understanding during the last decade, exciting improvements can be made in our ability to control turbulent flows and thus change their nature significantly, leading to novel drag and noise-reduction techniques; increased combustion efficiency; and control of separation, spreading, and mixing. Major advances in technology will be possible as a result of our ability to predict and control flows with turbulent zones.

- Continued rapid growth in the development of advanced computational fluid-dynamics procedures, together with the next generation of computer resources, will provide the opportunity to calculate and obtain a new level of physical understanding of complex three-

dimensional, compressible viscous flows. It will then be possible to optimize more effectively the design of high-performance aircraft, improve the forecasting of severe storm formation, attempt to predict global seasonal and annual climate changes, and realistically simulate and model fundamental processes in planetary and astrophysical fluid dynamical behavior.

- Powerful laser-based optical instrumentation techniques will be developed for the rapid, multipoint measurement of flow-field properties—pressure, temperature, velocity, species concentration. In conjunction with rapidly developing numerical techniques, these data will be manipulated to provide new types of information as well as increase the usefulness of large experimental facilities.

- In many technologically important fluid machines the flow is either separated or unsteady or both. With the help of modern instrumentation and computerized data-analysis techniques, we are beginning to understand the physics of these types of flows and how, often in combination, they can be used to improve the efficiency of technological devices ranging from heart valves to aircraft. We expect these possibilities to present a major research challenge in the coming decade.

- The challenges of combustion and reacting flows are likely to yield new understanding resulting in important applications in the near future. Control of soot and other pollutants will result from understanding of their production mechanisms. Understanding of the interaction between chemical kinetics and fluid instabilities will result in an understanding of deflagration and the transition to detonation. Applications range from improved fuel economy to fire safety.

- We expect to see major advances in our understanding of multiphase flow systems, including macroscopic and microscopic interface phenomena, which are of interest in both industrial and geological processes, for example, the stability of the liquid-liquid interface leading to fingering in oil recovery, convective processes in the ocean, and the formation of layered structures in magma chambers.

- There will be an increasing interest in the behavior of more-dense particulate systems, from the multiparticle interaction of finite clouds of particles to, more generally, the flow through porous media and filters based on the hydrodynamic interaction with their microstructure.

- Interdisciplinary cooperation in the study of basic cellular level biofluid dynamic processes in the presence of molecular forces will expedite explanations of such diverse phenomena as electrokinetic behavior in pores and membranes, the microstructure of osmosis, cell

division, cellular transport function, gel hydration, and fluid motion in intracellular tissue matrix. All lead to a better understanding of basic cellular physiological function.

- Increased computational and data-handling capability will permit assimilation and understanding of the massive data sets required to describe complex natural flow phenomena as well as those in man-made devices. For example, using satellites and shipborne instruments, global-scale investigation is now possible of the oceans and climate dynamics. Employing Lagrangian mathematical techniques and instruments that move with the fluid, we anticipate new views of turbulent dispersion; of the interaction between waves, turbulence, and mean flow in boundary layers; and in ocean-atmosphere circulations.

- The development of Monte Carlo computational techniques, which account for molecular motion in gas flows, will continue to be extended to higher-density flows, permitting meaningful modeling of highly nonequilibrium chemically reacting flow systems.

## FINDINGS AND RECOMMENDATIONS

### Principal Findings

#### SUPPORT STRUCTURE

- Support for basic research in fluid physics comes from a wide variety of sources. This is both a strength and a weakness, but the field suffers from the lack of an individual national identity. Despite the common technical threads that bind fluid physics, its basic research support is chaotic and limited. Considering its importance to technological development and its potential for contribution to the understanding of natural phenomena, fluid physics lacks sufficient visibility on a national scale and suffers from a lack of both amount and continuity of support from funding agencies, particularly for innovative new research directions.

- Many unique national experimental and computational facilities are not readily available to a large proportion of the research community. We do recognize and applaud the U.S. government's efforts to make time available for outside research in the National Aeronautics and Space Administration's (NASA) National Transonic Facility at Langley Research Center, in the 40 ft  $\times$  80 ft wind tunnel at Ames Research Center, as well as provide computer access through the Numerical Aerodynamic Simulation Program (NASP) also at Ames, and the National Center for Atmospheric Research (NCAR) Comput-

ing Facility in Boulder. However, we believe that considerably more could be done, producing benefits for both the research community and the facilities that are involved.

#### COMPUTATIONAL TECHNIQUES

- Numerous mathematical and experimental approaches are common throughout fluid physics, such as the use of asymptotic methods and laboratory flow simulations. In the last decade a new theme has emerged: the importance of the computer with applications that range from the rapid organization of data and their subsequent analysis and display all the way to the direct numerical simulation of the major features of some turbulent flows. This expanding capability provides rich opportunities for technological development and increased understanding of natural phenomena. It is now possible to use new scientific methods to tackle important but highly complicated phenomena, such as two-phase flow, which to date have been treated primarily from an empirical point of view. The mathematical techniques that have been developed and refined during the last 15 years have become increasingly important tools in advancing fundamental understanding of complex flows but also importantly in improving the methods for testing the results of numerical simulations as well. In the application of numerical simulation to technological problems, and most especially to aircraft design, the Europeans have been quick to acquire the latest high-speed computers and to implement the most advanced algorithms in the design of aircraft.

#### INSTRUMENTATION TECHNIQUES

- The past decade has spawned a remarkable growth in nonintrusive laser-based flow diagnostic techniques. Combined with equally spectacular developments in imaging, data storage, and manipulation techniques we have, during the decade, formed the beginning of what will become unprecedented advances in flow diagnostics cooperatively coupled to computational fluid dynamics.

#### EDUCATION

- The explosive growth of fluid physics into new areas involves increasingly interdisciplinary research. Acid rain prediction, gas lasers, blood flow, and the distribution of life in the sea are examples of strong interactions of fluid physics with chemistry, physics, and biology.

Fluid systems have motivated study of bifurcation theory, Lorenz attractors, and chaos, which are prominent in the study of physics and applied mathematics. This diversity of interests can be used to unify our understanding of fundamental fluid behavior and should be a more prominent part of university education. Education and university research in fluid physics is conducted primarily in engineering and applied mathematics departments in the United States. Last year only 1 percent of the Ph.D. theses in physics and astronomy in the United States were in fluid physics, and approximately 7 percent were in plasma physics, whereas approximately 30 percent of the engineering theses were on fluid-dynamics-related projects. This low emphasis on fluid physics in our physics curriculum has deprived physics research in this country of the opportunity to participate in many areas of technology that generate exciting new fundamental problems.

### **Principal Recommendations**

#### **RESEARCH SUPPORT**

- We urge that a mechanism be established to provide a continuing survey of research support in fluid physics vis-à-vis the field's national and intellectual needs. While we are unable here to make a detailed suggestion about the form of this mechanism, it should provide information that will be useful in identifying basic research areas in this nationally important field that are neglected by omission or as a result of not being within the immediate sphere of influence of a support agency. Particularly, new research directions of great promise could be identified earlier. Areas that receive excessive overlapping support could also be identified.
- We recommend a targeted research initiative to investigate and develop instrumentation for essentially simultaneous multipoint measurements of flow properties throughout large volumes. The instruments might be based on laser holographic methods, on multiprojection (tomographic) techniques, or on a combination of these and other as yet unexplored methods. The measurements are important to many national programs in fluid physics. It should be recognized that the instruments will be expensive, and hence it is imperative that sufficient resources be made available to the research community for their development and eventual use.
- We recommend the provision of funds and organizational mechanisms to make unique national fluid-physics facilities available to the university and nongovernment communities for basic research. Direct

allocations of time and other resources will be necessary in order to maintain an appropriate balance between basic research and urgent development programs and to assure steady operational funding of these facilities.

- We strongly recommend the expansion of the role of the National Science Foundation (NSF) in supporting basic fluid-physics research, with a particular emphasis on the support available for basic fluid-physics research related to engineering science. There is funding for fluid-mechanics research embedded in the atmospheric and oceanographic sciences programs. However, only extremely limited funds are available for basic fluid-physics research in NSF's Engineering Directorate. No funds have been available from the Physics Directorate.

#### EDUCATION

- In view of the pervasive importance of fluid physics in many areas of modern technology and the numerous unexplained phenomena associated with these technologies documented in this report, we strongly recommend that physics departments in this country consider the inclusion of a required undergraduate course in fluid physics. We similarly encourage engineering schools to consider a required upper-division undergraduate course in modern physics. This would be an important step in enhancing collaborative interdisciplinary relationships between the physical and engineering sciences.

- Fluid-flow instrumentation, especially optical techniques, are expected to continue their recent exciting progress. Unfortunately this will cause the state of teaching laboratory equipment in our universities to be even more out of date. The need for dedicated separate funding for modern laboratory equipment in fluid physics is at least as pressing as in other areas of science.

- Advances in numerical simulation and experimental techniques must not obscure the fundamental importance of analytical methods. These methods have been instrumental in advancing our understanding of complex flows and an aid in the development and verification of numerical methods for computing fluid flows.

#### GOVERNMENT SUPPORT, MANPOWER, AND UNIVERSITY RESEARCH

The major agencies that support external research in fluid mechanics and combustion are the Air Force Office of Scientific Research (AFOSR), Army Research Office (ARO), Department of Energy

TABLE 2.1 Fiscal Year 1983 Fluid-Physics Research Funding Levels (in \$ Millions)

AGENCY	Fluid Mechanics			Combustion			Totals		
	In-House	External		In-House	External		In-House	External	F.M. All
AFOSR	3.8	7.8		3.7	11.0		7.5	18.8	11.6 14.7 26.3
ARO		2.6			1.4			4.0	2.6 1.4 4.0
DOE		1.6			0.9			2.5	1.6 0.9 2.5
NASA	5	5		5	5		10	10	10 10 20
NSF (Atm. Sci.)		35 <sup>a</sup>						35	35 35 35
NSF (Eng.)		6.2			1.2			7.4	6.2 1.2 7.4
NSF (NCAR)		25 <sup>a</sup>						25	25 25 25
NSF (Physical Oceanography)		14.6 <sup>a</sup>						14.6	14.6 14.6 14.6
NOAA	10						10	10	10 10 10
ONR		14.5			6.6			21.1	14.5 6.6 21.1
NRL	6			1			7		6 1 7
TOTAL									138 36 174

<sup>a</sup> These figures include substantial amounts for major facilities such as researchships.



(DOE), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), National Oceanographic and Atmospheric Administration (NOAA), and Office of Naval Research (ONR). The FY 1983 research funding levels for these agencies and other in-house activities are reviewed in Table 2.1. These numbers are of course sensitive to one's definition of basic research and should only be used as an indication of the activity in fluid physics not as a definitive compilation.

For the external research support, generally about 50 percent goes to universities and 50 percent to private industry, with the exception of NSF. These support levels are approximate numbers and nominally only refer to basic research (i.e., DOD 6.1 funds). No attempt has been made to estimate the amount of contractor Independent Research and Development (IR and D) funding that perhaps should be added to these amounts. Our experience with the use of these funds leads us to believe that in practice only small amounts actually contribute to basic research. Also, no attempt has been made to characterize company and other private research in the field.

An estimate of manpower in the field of fluid mechanics and combustion research can be obtained by assuming an average of \$150,000 per principal investigator, which leads to a total of about 1000 full-time-equivalent principal investigators in fluid-mechanics research and about 250 in combustion research. Data from the National Bureau of Information indicate that approximately 900 Ph.D. theses are published each year in the general area of fluid dynamics. While the numbers given here are only rough approximations, they do indicate a notable national effort in the field.

There are large combustion and fluid-mechanics facilities maintained by the Air Force (AECDC and WPAFB, for example), NASA (Ames and Lewis, for example), NOAA, and NSF, which do not appear in the research support levels presented above. The funding level for these facilities comes to around \$250 million per year.

The historical trends in support levels are of interest. These trends are shown in Table 2.2 for fluid mechanics supported by two major research funding agencies. During the same period inflation has overwhelmed the small increases in support made available.

Despite the significant expenditures on fluid-physics-related activities, there is only limited direct support available for innovative or discretionary university research in fluid physics. Discretionary research support, such as represented by the Fluid Mechanics Program in the Mechanical Engineering and Applied Mechanics Divisions of the NSF Engineering Directorate (\$5.4 million per year in 1984), is very

TABLE 2.2 Historical Funding from Two Agencies for Fluid Mechanics

Agency	Fiscal Year								Change in Constant Dollars <sup>a</sup>
	1977	1978	1979	1980	1981	1982	1983	1984	
NSF <sup>b</sup>	3.4	3.5	3.5	3.7	3.5	3.9	4.2	5.4	-1%
AFOSR <sup>b</sup>	—	—	9.2	9.2	10.2	11.3	11.6	12.3	-8%

<sup>a</sup> Based on implicit price deflator, GNP; Business Statistics, 1982; Survey of Current Business, March 1984.

<sup>b</sup> NSF Mechanical Engineering and Applied Mechanics Division, Fluid Mechanics Program, AFOSR Directorate of Aerospace Sciences.

small and shrinking in terms of inflation-adjusted levels (Table 2.2). There are many areas of fluid physics that are simply neglected by the university research community owing to a complete absence of support. The large number of Ph.D. theses that are published per year in fluid physics is a result of the fact that fluid physics pervades a host of natural and man-made phenomena. They are not indicative of a high level of discretionary support for innovative, basic fluid-physics research. We believe that this situation is a scientific and technological mistake, with the potential for grave economic consequences.

#### DETAILED REVIEW OF THE BRANCHES, SELECTED TOPICAL SUBJECT AREAS, AND TECHNICAL DISCIPLINES OF FLUID-PHYSICS RESEARCH

In this section we have attempted to present a detailed review of fluid-physics research. First, there are fundamental-phenomena-related areas, which we call branches, that we found convenient for describing the field. Following are selected subject areas of current and future interest that we believe are topical and important but not clearly brought out by the division into branches. Finally, three technical disciplines that are of underlying importance to all of fluid-physics research are discussed.

##### Branches of Fluid Physics

##### COMBUSTION AND REACTING FLOWS

Chemically reacting flows in general, and combustion in particular, are branches of fluid physics for which the underlying equations

usually are considered to be the Navier-Stokes equations augmented by the equations of chemical kinetics. There are a number of aspects in which the scope of the field extends beyond this limited domain. For example, long-time correlations in kinetic theory, not described by the Navier-Stokes equations, have been inferred to affect certain turbulent ignition processes, and radiation-transport equations are needed in describing various radiant-interaction effects in combustion and radiation hazards from fires and explosions. However, the core of the subject is classical fluid mechanics coupled with chemical kinetics. In common with most other areas of fluid mechanics but in contrast with many other branches of physics, the underlying equations are known and the challenges are to ascertain the implications of the equations (and the values of the chemical-kinetic and transport parameters therein) for application to scientific and real-world problems of interest.

In a practical sense, combustion and reacting flows hold positions of high importance. The broad fields on which these topics have impact include those of recovery of energy resources, efficient utilization of energy resources, power sources for locomotion, atmospheric pollution, chemical lasers, waste disposal, and safety hazards. Numerous examples of relevance to these areas can be cited. Underground combustion, both reverse and forward, provides a potential means for large-scale recovery of oil from oil shale and of energetically useful gases from coal. Economies and improved efficiencies in natural gas, oil, and coal burners are achievable to some extent through advances in the understanding of combustion processes. Chemically reacting flows are of central relevance in the chemical process industries and in fuel refining. Emissions of oxides of nitrogen, of unburned hydrocarbons, and of soot and other particulates from both mobile and stationary power sources could be reduced by more rational means if better knowledge of salient combustion processes were available. Novel methods for disposal of hazardous wastes by incineration rely on knowledge of the fluid mechanics of the combustion processes involved. Fires are an ever-present threat to health and safety that necessitate continuing research on chemically reacting flows, e.g., to combat dangers associated with the rapidly changing mix of combustible materials in the modern urban environment. Importation of liquefied natural gas in large volumes has spurred research on the fire and explosion hazards of combustible clouds. Even nuclear reactors exhibit unique combustion hazards, as the Three-Mile Island incident demonstrated. Although this list specifically calls out practical problems, there are many scientifically challenging problems in the area that

are not tied directly to applications; moreover, improved scientific understanding increasingly is becoming a useful means for addressing the practical problems cited.

There are a number of significant recent developments in the area of combustion and reacting flows. In studies of burning of individual fuel droplets, conditions have been measured and largely understood under which a bubble is generated and grows within the liquid, shattering the droplet and in the process producing more efficient combustion with less production of soot and oxides of nitrogen. Modern diagnostic experiments, computational methods, and analytical methods together have given greatly improved knowledge of structures and propagation mechanisms of premixed laminar flames, thereby offering ideas, for example, for achieving reliable combustion under highly fuel-lean conditions in spark-ignition engines to improve performance. Significant improvements in the understanding of laminar-flame instabilities have been achieved, including interactions of hydrodynamic, diffusive, and gravitational phenomena to shed light on the reasons why Landau's classical prediction of absolute instability does not conform with experiment. Novel methods for calculating heat-release rates and rates of production of oxides of nitrogen in turbulent diffusion flames have been developed, contributing to understanding of possible methods for reduction of pollutant production. Improved understanding of extinction of diffusion flames has been achieved and applied to problems of flame stabilization and fire suppression. The first steps have been taken toward the development of rational descriptions of premixed turbulent-flame propagation, so that prospects exist for the emergence of a correct fundamental understanding of this intricate process. A number of recent developments in theory and experiment on flame spread along surfaces of fuels have improved our knowledge of mechanics of fire spread and led to new ideas on fire safety. Plenty of problems remain, and useful new methods for attacking them continue to be developed. The quality and number of young researchers in the area are increasing. Great challenges in combustion and reacting flows that are likely to be met and overcome at least partially in the near future may be listed as follows:

- Develop an understanding of mechanisms of flame propagation in areas ranging from fuel recovery to power production to fire safety.
- Develop descriptions of complex chemical-kinetic processes such as soot production that are simple and accurate enough to enable their overall rates and their influences on laminar-flame structures and dynamics to be understood and calculated.

- Develop firmly based and reliable methods for describing structures and propagation speeds of premixed turbulent flames, applicable to real combustors of practical importance.
- Clarify influences of chemical kinetics and chemical mechanisms on instabilities of reactors and flames.
- Develop improved descriptions of burning of sprays, including specifications of combustion regimes and more understanding of influences of turbulence.
- Demonstrate explicitly how pressure waves develop and interact in thermal explosions, in deflagration propagation, and in processes of transition to detonation.
- Clarify the relative importance of phenomena contributing to limits of flammability and of detonability, and describe near-limit propagation mechanisms better.
- Ascertain the relative importance of chemical and physical phenomena in contributing to flame extinction by different agents.

The list could be extended. In general, a broad range of methods, theoretical and experimental, must be brought to bear in finding solutions to these problems.

#### NON-NEWTONIAN FLUIDS AND RHEOLOGY

For over a hundred years, it has been customary in fluid mechanics to accept the Newtonian constitutive equation, i.e., the proportionality between stress and rate of deformation, as the standard fluid model that in conjunction with the laws of mechanics leads to the well-known Navier-Stokes equations of motion. Yet it has become increasingly apparent in recent years that there exist a great many fluids whose flow behavior differs in such a striking and fundamental way from that of their Newtonian counterparts that new constitutive equations need to be developed in order to properly model such systems theoretically. Examples of such fluids are blood, slurries, molten plastics, emulsions, suspensions of fibers, pastes, foams, and polymer solutions, so that it is being recognized that Newtonian behavior is the exception rather than the rule for a large class of substances having practical importances in a wide range of industrial processes.

Considerable effort has therefore been expended in an attempt to construct constitutive equations that relate the stress to the rate of deformation for such non-Newtonian materials, and indeed a large number of such equations have been proposed by various investigations. Unfortunately, these equations are, as a rule, quite complicated,

and it is far from clear at this stage which of them, if any, can properly account for the multitude of the observed non-Newtonian phenomena. Thus, an increasing amount of attention is currently being directed at evaluating the usefulness and applicability of existing constitutive equations rather than constructing new ones. This, however, is not an easy task, for, even when inertia can be neglected—which in the corresponding Newtonian case renders the Navier-Stokes equations linear—the resulting mathematical expressions are still nonlinear, owing to the complicated form of the constitutive equations, so that they can be tackled only via numerical techniques if the problem is anything but very simple. Even so, difficulties remain to be overcome.

Since the system of equations for the non-Newtonian fluids is, in general, higher order than for the Newtonian case, additional boundary conditions are needed that, however, are not always obvious. Also, questions regarding existence or uniqueness of the solution to the mathematical system as posed need to be addressed in conjunction with the numerical computations.

A dimensionless parameter that often plays a crucial role in determining the flow behavior of a non-Newtonian visco-elastic fluid is the Weissenberg number  $W$ , which is defined as the ratio of the relaxation time of the fluid to the characteristic time of the flow and which provides a measure of the non-Newtonian character of the system. Unfortunately, it has generally been found that conventional iterative numerical techniques fail to provide a solution to the appropriate set of equations and boundary conditions beyond a relatively low value of  $W$ , where the velocity field shows little difference from its Newtonian counterpart. It is not known at present whether the failure of these numerical solutions is due to deficiencies in the numerical schemes or whether it results from the mathematical problem having been ill-posed. Certainly, the resolution of this question is currently an important problem in this area of research.

Another non-Newtonian phenomenon, which is fundamentally different from everything that has been referred to above, is that of *drag reduction*, wherein it is found that the addition of certain macromolecules in minute concentrations (parts per million) to Newtonian fluids (typically water) can significantly reduce the pressure drop in pipes under turbulent flow conditions even though, in a viscometer, these solutions behave as Newtonian substances having virtually the same viscosity as the solvent. Drag reduction is therefore not only of obvious practical importance—it has already been employed in the Alaska pipeline as well as in many other instances—but the explanation of its origin would go a long way toward helping us to understand the

phenomenon of turbulent shear flow, which is currently the most important unsolved problem in fluid mechanics. Despite intensive effort on this topic, the factors that control this observed drag reduction are still not completely understood.

From a fundamental point of view, however, the key missing ingredient that inhibits rapid progress in this field is our incomplete understanding of the physics of non-Newtonian fluids and in particular the relationship between their physical constitution and their rheological behavior. A promising avenue for research that is currently being pursued involves constructing constitutive equations based on our detailed knowledge of the microscopic structure of the fluid, as is the case for polymer solutions, emulsions, and suspensions. Such an example is the "reptation" theory recently developed by deGennes and by Doi and Edwards. If successful, this approach should provide us with an in-depth understanding of the striking flow properties of non-Newtonian fluids—which are often very unlike those observed with Newtonian substances—and even help us to discover new non-Newtonian phenomena or construct fluids with preassigned flow characteristics.

#### VORTEX-DOMINATED FLOWS

The study of vortex-dominated flow fields aims to describe situations, steady or nonsteady, in which the velocity induced by strong vorticity is the central feature in establishing the flow field itself. Such flows are intended to contrast with those where, for example, weak vorticity is transported by a strong irrotational flow, and hence, to a considerable extent, the problem may be considered a linear one. Familiar examples are thin airfoil theory, lifting line theory, and most lifting surface theory. Examples of nontrivial but well-known vortex-dominated flows are the vortex pair and the vortex ring.

Several classes of vortex-dominated flows are described below according to the physical origin and interest of specific problems rather than from the standpoint of their analytical or computational difficulties.

##### *Disturbance of Initially Rotational Fields*

A wide variety of problems involve an initially strong vortical field that is disturbed by boundaries or body forces. A classical example of such a physical situation is the flow produced by a finite wing moving through a strongly rotational field, studied initially by Karman and

Tsien. This phenomenon appears to be of great current importance in the behavior of blades in the compressor and turbine components of aircraft gas turbines. Another important example under active development is the flow of initially rotational fluids in ducts and channels having complex bends and changes in shape of their cross section. This general field has become known as secondary flow and is of great interest in the investigation of ducts leading to the inlets of aircraft gas turbine power plants.

#### *Vortex Fields Generated by Highly Loaded Wings and Bodies*

One of the most spectacular and important examples of vortex-dominated flows arises in the flow fields generated by highly loaded wings and by bodies at high angles of attack. Both research workers and designers have accommodated their intuition and understanding to the simplifications and results of lightly loaded wing and body theory, but frequently the fields of heavily loaded wings and bodies bear little resemblance to their classical counterparts. The tendency of the strong vorticity shed from heavily loaded wings to roll up quickly into rather concentrated vortex tubes leads to unusual trajectories, intense induced velocity fields, and frequently to asymmetric or nonsteady flow patterns and forces. The understanding and description of these complex flow fields is one of great importance in estimating the performance of high-speed aircraft, particularly high-performance fighters.

In many practical instances the situations described above involve three-dimensional flow separation, and, as is well known, the tendency for an asymmetric flow to be associated with a symmetric geometric configuration is aggravated. The influence of the strong vortices on the separation line becomes a central issue. Diligent and continuous research, both experimental and theoretical, is required to achieve an acceptable degree of quantitative understanding.

#### *Geophysical Flows*

Important flow patterns as they occur in the atmospheres of the Earth and other planets may be considered as vortex dominated. Among the important members of this group are the general problem of weather prediction, tornadoes, fire storms, and possible weather modification. The details of geophysical flows are covered elsewhere in this report.



### *Contained Vortices*

The ability of many practical devices to function is dependent on the generation and stabilization of vortices or groups of vortices within fixed geometric boundaries. Centrifuges, ultracentrifuges, small particle separators, and the vortex containment of nuclear reactions are familiar examples. In other circumstances the vortices occur inadvertently; an interesting example is the formation of a strong axial vortex in some solid propellant rocket motors, the effects of which may lead to dynamic instability of a missile.

### HIGH-SPEED FLOWS

There are several opportunities for major advances in high-speed flows that extend the developments of the past decade. These past developments have been focused in two primary technology areas. One is the development of highly efficient commercial and military transport; the other is the development of highly maneuverable fighter aircraft. These developments will continue primarily from advances in our understanding of separated flows, from our special knowledge of new aerodynamic design procedures, from our beginning understanding of, and thereby our ability to control, turbulence, and from the continuing growth in the use of computers to solve aerodynamic flow fields (addressed elsewhere).

In many flows of technological interest the flow is either separated or unsteady or both. We are beginning to understand the fundamental physics of these separated and unsteady flows and how, often in combination, they can be used to improve the efficiency and performance of technological devices.

Both steady and unsteady mechanisms can be used to generate separated flows. These separated flows have special characteristics that have made them important in the design of supersonic aircraft. We are just beginning to understand the nature of the separation process, the fundamental physics of these flows, and how they can be generated and utilized through unsteady surface motions.

We are now beginning to understand better the fundamental physics of the process of transition to turbulence, and through that understanding we are beginning to develop controls that suppress this transition. These controls range all the way from acoustic input to the boundary layer through the removal of a substantial portion of boundary layer from the surface.

It has been known for some time that the aerodynamic designs that operate at high subsonic Mach numbers are most efficient if they can avoid the generation of shock waves. But such flows are mathematically isolated from one another and were, for some time, thought to be impractical. It has been demonstrated over the last decade that these mathematically isolated solutions are of practical value, and special techniques have been developed to find them. These techniques have now been generalized to the point where they can be used routinely in the design process, guaranteeing that the extremes of the transonic design envelope can be reached.

By the end of the century we can expect a significant increase in the fuel economy of the present-day commercial aircraft. This increase will occur through a number of design innovations, and the aerodynamics of high-speed flow will contribute roughly 20 percent of this improvement. For this reason alone, the fundamental physics of these flows is especially important. In addition, there are many devices whose designs may be altered radically if one turns from steady attached flows to unsteady separated flows to improve their performance. Our understanding of the physics of these unsteady separated flows is just beginning and is especially important.

#### MOLECULAR AND STATISTICAL PHENOMENA

Molecular-scale phenomena are basic to all of fluid mechanics. Transport properties such as diffusion coefficients, interface transport phenomena, and non-Boltzmann energy-level population distribution in chemically active flows are examples.

In the past decade one of the developments in this area has had an important influence on chemical physics. Flow cooling, or the expansion of a sample and a carrier gas through a nozzle to millikelvin temperatures, has been developed based on aerodynamic molecular-beam techniques. A rapidly increasing momentum-transfer-collision cross section at low temperatures, which overwhelms the density decrease due to the expansion, allows collisions to be active throughout the flow. The very low gas-phase temperatures that are achieved permit studies of collisions between isolated energy states through state-selective excitation of crossed molecular beams.

There have been notable recent advances in statistical phenomena related to biological problems. Phenomenological coefficients in the Kedem-Katchalsky equations (equations coupling water and solute movement across biological membranes) have been derived from more fundamental equations describing diffusion and convection in biologi-

cal pores. The role of endothelium as a transport barrier for macromolecules has been elucidated through the use of quantitative models to examine the change in arterial wall permeability to cell turnover (dying of endothelial cells), vesicle transport, and the opening of the intercellular junctions between cells. The models have been used to explain why minute changes in endothelial structure can lead to localized regions with twofold increase in lipoprotein uptake.

Another subject that has received attention in the past, but now appears particularly ready for rapid development, is the use of Monte Carlo techniques for handling gas flows at relatively high pressures with detailed accounting of internal-energy-state transitions. Appropriate collision probabilities can be generated or verified by the selected-state chemistry studies described above. Advances here would be an important step in describing highly nonequilibrium chemically reacting flows, which are important in applications such as high-energy chemical lasers.

We expect that there will be exciting developments in the biological application of statistical phenomena. Osmosis has still only been explained from a macroscopic thermodynamic viewpoint. A microscopic theory on the length scale of the membrane pore diameter is still needed. There is also no microhydrodynamic theory describing the transition from deterministic to diffusion-dominated particle motion (particles with diameters of 100 to  $10^{24}$  Å). In general, problems in biological transport of water, ions, and macromolecules involve novel boundary conditions for the surface layer of epithelial and endothelial cells, difficult problems in subendothelial interaction, and a variety of new phenomena such as endocytosis and exocytosis associated with the biophysics of the plasma membrane of the individual cells.

#### VISCOSITY-DOMINATED FLOWS

The area of viscous fluid mechanics where the primary force balance on a fluid element is between pressure and viscous stresses and the inertia of the fluid element is small is often referred to as low-Reynolds-number hydrodynamics. This basic force balance is satisfied in a wide variety of applications involving multiphase flow, thin films, molecular diffusion, interface phenomena, and colloid and membrane science.

Stimulated by the work of G.I. Taylor on the swimming of microorganisms, many of the newer problems in low-Reynolds-number fluid motion have been motivated by biological applications. This includes such diverse problems as the swimming of sperm and other flagellar or ciliated organisms; the movement of the cellular components of blood

in the microcirculation; the motion of fluid or particles in biological ducts lined with cilia such as the oviduct, the small intestine, or the intestine; trachea; and the gaseous exchange in lung alveoli.

During the past decade interest in low-Reynolds-number hydrodynamics has grown tremendously, spurred by numerous applications in the chemical processing industries, new biological problems, and the advent of numerical solution techniques that could treat a much wider variety of particle- and boundary-interaction problems than could be handled by purely analytical methods. The chemical processes involve such problem areas as modern filter technology, aerosols and sprays, sedimentation of particles and colloidal suspensions, fluid-fluid separation processes, electrokinetic and osmotic phenomena, hydrodynamic chromatography, surfactant technology, and molecular transport through biological and synthetic membranes. The new biological applications derived from the need to obtain better understanding of a variety of cellular level biological phenomena, such as the vesicular transport of lipoproteins across arterial endothelium (thought to be related to arterial disease), the deformability of cells due to fluid motion, and the stability of membranes in the presence of fluctuating fluid stresses. Most of these problems are of an interdisciplinary nature and call for the collaboration of engineers, physicists, and biological researchers. Fluid dynamicists with a chemical engineering background, in particular, have contributed significantly to the many recent advances summarized below. This has led to the birth of a new field of study, "physicochemical hydrodynamics," in which low-Reynolds-number hydrodynamics and interfacial fluid mechanics are inextricably linked with a variety of physicochemical phenomena.

The requirements of the chemical and biological applications have necessitated the development of new solution procedures for the treatment of the more complex boundary-value problems that are encountered in these applications. Thus the treatment of small fluid drops near interfaces or droplet coalescence in fluid-fluid separation processes requires a solution technique that can be used to describe not only the fluid motion but also the unknown large-amplitude deformation of the interface and/or the drop due to this motion. The movement of proteins and other molecules in the intercellular channels of biological cell layers or particle entrance behavior in membranes and nucleopore filters requires the solution of strong hydrodynamic interaction problems in which the particle motion is greatly influenced by the boundary geometry.

In addition, a number of new low-Reynolds-number hydrodynamic phenomena have been either discovered or explained in the recent

past. It is now realized that there are separated flow regions between particles when the separation is sufficiently small and that this flow separation will have an important effect on the heat- and mass-transfer characteristics of a bed of particles. It is now understood why flexible particles in the absence of inertia will migrate toward the centerline, why a small amount of inertia will cause a particle to migrate to an off-axis equilibrium position, and why finite axial clusters of neutrally buoyant identical particles will break up and form aggregates. The theory for a tiny particle being convected down a tube subject to Brownian motion has led to the development of hydrodynamic chromatography, a separation classification procedure for identifying particles by size.

The sedimentation of particles and dilute colloidal suspensions exhibits several fascinating characteristics that were not previously understood. It has now been shown theoretically why the settling velocities of a fixed array and a random statistical array of particles obey a different power law as a function of density, how orientable particles settle differently than spheres, and how the latter are affected by Brownian motion. The importance of boundaries in the settling process is greatly accelerated in a long slender channel by tilting the channel away from the vertical. The mechanism for this behavior has recently been explained and is currently under study as an industrial separation process.

It is evident that much of the growth and progress in low-Reynolds-number hydrodynamics in the past few years is the result of the cross-fertilization that has occurred between researchers in different disciplines as a source of new observations, creative applications, and methods of solution. In most cases low-Reynolds-number hydrodynamics is one essential ingredient of a larger problem. Biological problems, especially at the cellular level, will continue to be a major source of new research primarily because there are so many different cellular functions and unexplained experimental observations. There is still no accepted theory to explain the microstructure of osmosis, the detailed flow and concentration patterns that exist at the opening to pores in biological and synthetic membranes. Electrokinetic phenomena will be important both at the exterior surface and within the pore itself.

An area that has received relatively little attention because of its complexity is the two-phase convective transport of submicrometer particles that are strongly influenced by Brownian motion. At present much of the work in this area is limited to deterministic motions upon which a weak Brownian motion is superposed. The transition between

deterministic and statistical behavior is also important in the sedimentation of particulates and the study of colloidal suspensions. Thus far the theory of suspensions has only been applied to dilute systems. The effect of electric double layers, particle deformability, and orientation are further topics of considerable current interest in research on colloidal suspensions and emulsions. Progress in many of these problems would be enhanced by closer collaboration between fluid dynamicists and statistical physicists.

The recent success in treating droplet and fluid interface problems with large deformations has paved the way for examining a variety of phenomena associated with aerosols and fluid-fluid separation processes. This research will also be valuable in studying the behavior of surfactant molecules at interfaces, droplet coalescence, deformation of biological cells due to fluid stresses, and related problems.

#### STABILITY

Stability of fluid flows is studied, in the first instance, to determine the realizability of proposed flow fields. The main issues historically concerned the onset of thermal convection and the transition to turbulence of shear-dominated flows; more generally the purpose is to predict the possible forms of motion that can branch from a given motion and the sensitivity of these motions to disturbances. In this regard, the subject is now viewed as intrinsically linked to bifurcation theory, the study of the branching processes in nonlinear systems. This broadens the scope of the investigations to inquiries dealing with the forms of "generalized equilibrium states" that arise after the onset of stability.

Stability theory, by its very nature, seeks to predict the circumstances leading to qualitative changes in flow patterns. Consequently, stability theory is a subject of practical technological importance, in that qualitative information concerning industrial processes derived from stability considerations often can be incorporated in design decisions with decisive effects, and the promotion or suppression of fluid-dynamical instabilities is often a crucial technological issue.

Motions on geophysical scales, including the dynamo problem, mantle convection, and atmospheric and oceanic current systems, frequently take forms determined by the instability of equilibrium flows arising from fundamental force balances. Useful insights and predictions of these forms can be found using stability theory. Consequently, this branch of fluid mechanics figures prominently in oceanography, meteorology, and planetary sciences. It is similarly important in

astrophysics, in problems concerning stellar convection and galactic structure, as well as in similar questions of considerable interest and importance.

Modern advances in this subject have been marked by major changes in conceptual framework as the nonlinear behavior of fluid systems became the focus of an increasing body of work in stability theory, and this has led to much more satisfactory connections between theory and physical experiments. The theoretical advances have been made possible by developments in bifurcation theory, by systematic exploitation of multiple-scale and related singular perturbation techniques, by the advent of inexpensive large-scale computation, and by the introduction of increasingly sophisticated experimental techniques.

Important new physical effects have been explored, in some cases leading to significant reassessments of phenomena previously misinterpreted. The effects of surface forces (Marangoni effects) in driving convective instabilities, and effects arising in mixtures (such as double-diffusive instabilities of importance in oceanography, astrophysics, and technological applications) previously treated as single-component fluid systems, have been systematically explored. Magnetohydrodynamic and electrohydrodynamic instabilities, instabilities in liquid crystals, and instabilities induced by complicated indirect effects, such as nonlinear wave-mean-flow interactions, all are examples of new forms of instabilities that were unknown 10 or 15 years ago.

Analytical nonlinear theories, originally limited to weakly nonlinear perturbations of a single-instability mode, have been extended to allow for more complicated spatial behavior generated by multiple-mode interactions. Considerable progress has been made along these lines for Benard convection and for Couette flow between rotating cylinders. Extensions of this kind permit information about convection pattern selection to be inferred; this very basic aspect of the motion cannot be obtained from the classical theory. Work dealing with imperfections, that is, slow modulations of motion patterns generated by distant boundaries or nonideal forcing omitted in classical linear theories but having considerable impact on observed patterns of motion, has been appearing.

Stability work, including analytical theory, has always required a great deal of computation, and the level of computation has increased with the complexity of the newer problems, particularly perturbation analyses of the kinds mentioned in the previous paragraph. These studies could not have been undertaken without fast computers. Computers have been the essential tools in other modern stability studies. By numerically tracing bifurcating solutions, the restriction of

weak nonlinearity has been removed, at least in some problems. Thus, the instability of fully nonlinear waves in Poiseuille flow, allowing for some (weak) three-dimensional unstable modes, has been investigated, as have the fully nonlinear instabilities of other flows of classical interest and scientific importance. In addition to these investigations, which deal either with the Navier-Stokes or the Euler equations, computer studies have been made of the evolution of model systems, in which the solutions of the governing equations are represented by a spectral decomposition in spatial variables, and the resulting infinite system of ordinary differential equations (in time) are severely truncated. Integrations of the resulting ordinary differential equations, coupled with bifurcation analyses, have revealed bifurcation sequences leading to chaotic motion. In some cases, the results are known to be misleading (for example, the Lorenz equations modeling thermal convection) but seem to be confirmed by integration of the full governing equations in other cases. Thus, the full equations for double diffusion show a period-doubling bifurcation sequence, a well-established route to chaos, and a five-mode truncation model reproduces this behavior.

Large-scale computation, coupled with careful interpretations based on the mathematical framework underlying stability and bifurcation analyses, is likely to yield an extremely rich body of information in the next 10 to 20 years. Almost certainly, the groundwork already laid will produce a much more complete understanding of pattern selection and forms of equilibrated motions deriving from instabilities. Considerable progress can be expected on the problem of the transition to turbulence in shear flows and even greater progress on the transition to turbulence on flows, such as Benard convection, that are destabilized by body forces. It is possible that further links will be forged between the routes to chaos established for systems with a finite number of degrees of freedom and continuous systems. If so, greater insights will be gained about the continuous instability that is fluid-dynamical turbulence.

#### TURBULENCE

Turbulence appears in nearly all flowing continua when inertia is dominant relative to the microscopic momentum transport mechanism. It is responsible for most technologically significant drag, heat, and mass transfer and makes life possible on Earth by controlling the distribution of food, heat, moisture, and light in the biosphere. Turbulent heat and mass transfer in the magma are probably involved in crustal movement and temperatures. Turbulent heat transfer plays a



controlling role in the dynamics of stellar atmospheres and of interstellar gas clouds and is probably implicated in the gravitational condensation of matter from these clouds.

The study of turbulence has had as its goal both a philosophical and a quantitative understanding of the physics of turbulent flow, so as to enable numerical predictions to be made in all of these areas.

Turbulent transport is usually several orders of magnitude larger than molecular transport, so that when present, it is dominant. Since it is implicated in so many areas of vital concern to humankind, it is clearly important. While the grosser aspects of turbulent behavior are thought to be understood in crude qualitative terms, many of the more subtle aspects are understood poorly or not at all; our ability to make quantitative predictions is extremely limited, and precision is poor.

Although turbulence is recognized as the last great unsolved problem of continuum physics, until recently it was largely abandoned by mainstream physicists. Developments in the last half-century have been largely due to the engineering community, mathematicians, meteorologists, and oceanographers—those who either could not afford to ignore the area or were fascinated by it.

During this period, vast quantities of data were collected, although not always with imagination. The approach was almost entirely statistical. The result was a reasonable grasp of turbulence behavior in many situations and enough understanding of the physics to permit data taken in different circumstances to be placed on a common footing. Several analytical approaches related to techniques used in quantum field theory were applied to the problem; these have resulted more in added insight than useful computational techniques or major theoretical breakthroughs.

The advent of large-scale computing has made it possible to solve the Navier-Stokes equations exactly for some simple turbulent flows. This has made accessible quantities that are difficult or impossible to measure but has not replaced experiment; the computations have their own problems relative to the influence of initial conditions on convergence and differencing errors, and flows complicated enough to be practically interesting are and will remain for some time beyond economic reach. These exact simulations are limited to relatively low Reynolds numbers; large eddy simulations avoid this limitation by computing large scales exactly and modeling small scales. Otherwise, the large eddy simulations suffer from the same limitation as the exact simulations.

Invariant modeling, second-order modeling, and related techniques have been developed to make practical computations. These tech-

niques close the hierarchy of moment equations at various levels (reminiscent of the BBGKY techniques of statistical mechanics). The most interesting of them produce sets of equations for second moments reminiscent of nonlinear diffusion reaction equations or of nonequilibrium thermodynamics of mixtures. Much of this modeling is ad hoc, although it has been possible to base some of it on first principles *a posteriori*. This modeling describes small departures from equilibrium and has corresponding limitations. It has been practically useful, although it has been oversold. More to the point, the construction of the models has been valuable, since it has resulted in much more careful examination of the data and evaluation of the phenomenology and in some cases the taking of interesting new data.

The physics community has been particularly stimulated by strange attractors, which explain how some deterministic mechanical systems with three or more degrees of freedom can display apparently chaotic behavior in time and exquisite sensitivity to initial conditions. A number of interesting (in some cases general) properties of such systems have been uncovered. These ideas may explain how turbulent flows can seem to be stochastic, although the extension to continua, and to spatial (as opposed to temporal) complexity, is intuitive. Some light has also been shed on the early transition process. It remains to be seen whether these ideas will help with calculations of fully developed turbulence.

Although it has been known for at least 30 years that most turbulent shear flows contained recurrent structures organized on the scale of the flow, little was done with this information. Recent evidence from visualization indicates that these structures are more remarkably coherent than anyone had suspected. The two-dimensional shear layer is not particularly characteristic of other turbulent shear flows, and the relative importance of these structures differs widely from flow to flow. The structures appear to result from instability, either as remnants of the initial instability that formed the flow or as an instability of the fully developed flow, sometimes both in the same flow (as in the wake). There is currently great interest in these structures, their identification, etiology, and prediction, sometimes to the exclusion of the rest of the flow, which remains chaotic. Fortunately, most workers recognize that turbulent flows contain both order and disorder, and techniques are necessary that can encompass, and profit from, both.

New statistical techniques are being applied to measurement, notably conditioned sampling to reduce the form of the coherent structures. These can be powerful if carefully used, with proper attention to statistical stability and bias introduced by the condition. These tech-

niques supplement, but do not invalidate, conventional statistical approaches, which often will produce the same statistical information with different accuracy and efficiency.

Probably all the approaches currently under investigation will continue so for a while, and others will be added or take their place. We have little faith in breakthroughs in general, and particularly in a field as old as this one; we believe that progress is most likely to come in small increments by increased physical understanding, probably from interaction between careful machine calculations and modeling of various types compared to experiments. Much insight will probably come from investigation of the stability characteristics of turbulent flows and of models and from the inclusion of coherent structures in models. The dynamical systems approach seems very likely to make further contributions, if only to transition. Recent Soviet work relating coherent structures and the dynamical systems approach may bear fruit.

The geophysical aspects of turbulence are an interesting special case. The atmosphere and oceans of this and other planets are the greatest natural laboratories for turbulence. There are fully ten decades of scale between the large weather systems and the scale of molecular diffusion. The key problem of geophysical fluid dynamics is first to understand the separate dynamical nature of motions across this range of scales and then to synthesize them into one vast interacting and cascading spectrum. It is not an exaggeration to say that weather prediction, the understanding of the general circulation of the atmosphere-ocean system, and the evolving states of climate are all problems of fluid-dynamical turbulence.

There are two distinct kinds of geophysical turbulence: small-scale, three-dimensional turbulence and large-scale turbulence whose freedom is reduced by stratification and planetary rotation. In fact, when the many geophysical constraints like these are added, the turbulence problem becomes intimately related to both wave propagation and flow stability.

Of particular interest is the manner in which turbulence and waves interact in systems with buoyancy and rotation. These chaotic motions, in addition, interact with the general circulation of the fluid in a strong manner. A key question under current study is the way in which eddies and the mean circulation mutually influence one another. We are now approaching a clear dynamical understanding of diverse phenomena like the Southern Oscillation, stratospheric sudden warming, and quasi-biennial oscillation of the atmosphere and the wind-driven gyres and deep thermodynamically driven circulation of the oceans.

At smaller scales turbulent mixing of the oceans, in the vertical sense, slowly but persistently determines the gross structure of the temperature, salinity, and trace chemistry. Recent improvements in free-falling instruments have documented this turbulence, but we have yet to describe clearly its bulk effect on the oceans. .

Studies in atmospheric and oceanic dynamics have, in fact, been the origin of a range of nonlinear physics and mathematics problems, for example, with interactions and Lorenz attractors in systems with few degrees of freedom.

#### BUOYANCY-DRIVEN MOTION

##### *Convection in Nature*

Fluids of nonuniform density are subject to buoyancy forces, under fields of acceleration or gravity. The density variations may originate in compositional differences, suspended particles, phase changes, or temperature variations. The range of phenomena is vast. In meteorology, cumulus clouds and the global-scale Hadley circulation are examples of convection driven by latent and sensible heat. Evaporation and cooling at the sea surface both drives convection that ventilates the depths and, with a time-scale of thousands of years, determines the basic stable density field of the oceans. Where the fluid density is determined by two or more separate components (like salt and heat in the ocean), double-diffusive convection can occur in which rapid diffusion of one component destabilizes the fluid, despite its overall stable density profile.

The geological evolution of the Earth's mantle and crust is an instance of convection driven primarily by radioactive heating from below. Fluid models (both theory and laboratory experiments) of these tectonic processes have led to an enormous unification of geology, with practical implications from fossil fuels to earthquakes. At smaller scales the flow and convection of fluids in the presence of crystallization is beginning to explain the structure of magma chambers, spreading centers, and some aspects of vulcanism.

Turbulent buoyant convection is an especially difficult problem relevant to the transfer of heat, moisture, and momentum in the surface layers of the atmosphere. Turbulence closure theory, and other parameterization schemes, are being developed to describe the turbulent heat flux and the evolution of the spectrum of velocity.

### *Suspended Particles*

The settling of small particles under gravity through a quiescent liquid is an important physical operation that is used extensively in a large variety of industrial operations. Unfortunately, the process is a very slow one, especially when the particles are small, and hence there exists a need for designing settling devices in which the particle retention times are minutes rather than hours or days. One class of such devices, termed supersettlers, takes advantage of the Boycott effect according to which particles settle a great deal faster where the walls of the settling vessel are inclined rather than vertical. Strong buoyancy-driven convective flows are, however, set up in such inclined settling vessels that may decrease the efficiency of the process; hence the detailed investigation of these flows is of both academic and practical interest.

### *Gravity Currents*

The term gravity or density current denotes the flow of one fluid within another, caused by the density difference between them. The fluids are usually miscible, and the mixing that results can play an important part in the dynamics of the flow. Gravity currents are encountered in situations of geophysical and atmospheric interest and have important applications to aircraft safety, atmospheric pollution, or industrial accidents involving the spread of a dense gas—such as liquefied natural gas—from an accidental release.

### *Convection in Materials Processes*

Temperature- and concentration-induced buoyancy-driven flows occur frequently in materials-processing operations such as crystal growing, with both desirable and undesirable consequences. Convection of course increases the overall transport rate of heat and mass and hence the growth rate; on the other hand, the morphology of the solid is usually affected adversely.

## INTERFACE PHENOMENA

Flows with interfaces between two or more fluids occur frequently in nature and play an important role in a wide variety of physical phenomena. All of these share the common feature that the domain of interest involves a boundary of unknown shape whose evolution,

generally in time, is one of the primary goals of any theoretical or experimental investigation on the subject. The problem of determining this interface often requires novel experimental, analytical, or computational tools.

We list below some of the more important topics that are being actively investigated at present.

#### *Deformation and Breakup of Small Drops in Shear Flows*

In many industrial processes it is often required to disperse one liquid phase into another with which it is immiscible. One wishes then to design an appropriate mixing device and to determine the power necessary to ensure that the size of the largest drop comprising the dispersed phase does not exceed a given value.

#### *Breaking of Waves*

When designing harbors and coastal breakers, one wishes to determine the shape of the waves as they advance onto the beach, find out where they break, and then calculate the energy that is released. In view of their potential for causing great damage, the behavior of tsunamis is particularly relevant in this connection.

#### *Sediment Transport*

This involves the modeling of ripples and dunes as well as the study of coastal sediment processes. The transportation of solid-liquid suspensions, such as slurries, in pipelines and the determination of the many possible flow regimes that can occur are also topics of considerable current practical interest in this area.

#### *Solitons*

Solitary waves, on the surface of shallow layers as well as in layers of infinite depth containing regions of nonuniform density, are currently being studied extensively because of their remarkable property of being able to propagate without change of shape and to maintain their identity on colliding either with a stationary object or with another such wave. Solitons play a central role in many phenomena of geophysical significance.

*Spreading of Liquids on Solid Surfaces*

This topic is of considerable theoretical interest because it involves the motion of the contact line, i.e., the intersection between two immiscible fluids and a solid surface. Clearly, this motion, which is certainly observed experimentally, violates the universally accepted no-slip boundary condition, which must therefore be replaced by something more complicated. Coating flows, which are of great importance in the photographic industry, also involve the motion of contact lines.

*Air-Sea Interaction*

The atmosphere and oceans form an interlinked system. The transport of gases, heat, moisture, particulate material, and momentum across the air-sea interface is a phenomenon relating to the evolution of climate, weather prediction, and the distribution of trace chemicals and man-generated pollutants. On both sides of this interface lie turbulent boundary layers. The interface itself is a convoluted surface, with breaking surface waves that inject bubble clouds into the sea below. Recent advances in observational oceanography and boundary-layer meteorology are leading to qualitative improvement in our understanding of the small-scale mechanism. For problems of global scale, we are coming to rely on remote sensing, particularly from orbiting satellites, to provide air-sea transfer maps.

## SOUND GENERATION AND PROPAGATION

Generally the field of acoustics is well understood provided we stay out of the nonlinear range. The transition from linear acoustics to nonlinear acoustics and the interaction of acoustic phenomena with flow fields are just beginning to be understood. One of the items mentioned earlier in the section on High-Speed Flows—the control of turbulence—will also play a fundamental role in the control of the generation of sound by jet aircraft. It is generally the turbulence of the jet that creates the largest portion of the sound field, and this control will allow a further reduction of the perceived noise of jet aircraft. The radiated acoustic energy of jet aircraft was reduced nearly 1000-fold during the 1970s, mainly by reductions of jet velocity, which yielded the collateral benefit of much improved propulsion efficiency. Another factor of this magnitude could be available if we can control the jet mixing process. As the noise from the inlet and jet exhaust become

suppressed, the next dominant noise will be due to the turbulence on the wings and fuselage. The process for controlling the turbulence of the aircraft is important not only to the reduction of drag of the aircraft but also to the reduction of the internal noise of the aircraft.

The transition from linear to nonlinear acoustics is important in several fields of technological interest, including the fracture of rocks by high-speed water jets. We still do not know the fundamental physics of the focusing of acoustic waves to form caustics and cusps in caustics.

The unsteady body forces that occur principally in helicopter rotors, engine compressors, and propellers are also important generators of noise. Basic understanding of the mechanism of noise generation, and the application of this understanding to problems such as the interaction of a helicopter rotor blade with the previous blade's trailing vortex, has led to considerably quieter aircraft and helicopters.

The acoustic analogy that provided the insight needed to greatly reduce jet noise is now aided and abetted by the understanding being provided by the application of rapid distortion theory. This theory linearizes about a mean steady flow and assumes that the characteristic time for the interaction of this flow with its unsteady variations is short compared with the characteristic time for the decay of this unsteadiness. The application of these ideas accounts for sources of acoustic radiation beyond those recognized in the original acoustic analogy.

#### RADIATION HYDRODYNAMICS

One particular subfield of fluid dynamics that is both intellectually challenging and of great importance is radiation hydrodynamics, which also goes by the names radiation-coupled flows and radiation-induced flows. This is basically the study of hydrodynamic phenomena at very high temperatures, in which the thermal radiation field associated with matter affects the dynamics of the fluid. The importance of thermal radiation in fluids problems increases as the temperature is raised, primarily because the radiation energy density associated with a Planck distribution varies as the fourth power of the temperature. At low temperatures (say, room temperature) radiation effects can generally be completely ignored in the fluid flow context. One important exception is the radiatively driven flow in some planetary atmospheres. At moderate temperatures (say, thousands of degrees) the role of radiation is primarily one of transferring energy by radiative processes. At higher temperatures (say, millions of degrees) the energy density and pressure associated with the radiation field become comparable to



or even dominate the corresponding fluid quantities. In this case, the radiation field significantly affects the dynamics of the field. Fluid flow with explicit account of the radiation energy and momentum contributions constitutes the character of radiation hydrodynamics. The relevant fluid equations, namely, the energy and momentum balances, contain additional terms accounting for these radiative contributions. These terms in turn are computed from an auxiliary equation, the equation of radiative transfer, which is a kinetic equation describing the flow of photons in phase space. Thus radiation hydrodynamics involves the simultaneous solution of the fluid equations and a kinetic equation. Because of the high temperatures involved, viscous effects can generally be ignored, and often heat conduction can be ignored as well.

In addition to the inherently rich physical and mathematical content of these equations, the study of radiation hydrodynamics is of great practical importance. It is clear that applications of this field will involve physical phenomena at very high temperatures. The primary applications involve three areas of great import to mankind. The first is found in astrophysics, where the underlying purpose is to obtain a better understanding of our universe. The second involves national defense. A thorough understanding of radiation hydrodynamics is essential for predicting nuclear-weapons behavior and effects. The third significant application of this field is found in the energy arena. Any calculation of inertially confined fusion concepts, be it laser- or particle-beam-driven, must be based in large part on the equations of radiation hydrodynamics.

Because of the complexity of the radiation hydrodynamics equations, very few meaningful analytical solutions can be found. Thus the challenge has been, and continues to be, the development of accurate general-purpose numerical methods for solving the coupled set consisting of the fluid equations with radiation terms and the equation of transfer. To date, both Eulerian and Lagrangian formulations have been developed, in one- and two-dimensional generality. However, the corresponding treatment of the radiation field has been limited to diffusion (moment) approximations to the equation of transfer, as well as the generally prohibitively expensive Monte Carlo method. It is becoming increasingly clear that the diffusion approximation is simply not accurate enough to describe certain physical phenomena adequately. Thus what is required on the near to medium future time scale is the development of Eulerian and Lagrangian methods for fluid flow, coupled with more accurate (than diffusion theory) and less expensive (than Monte Carlo) solution methods of the equation of transfer.

Ideally, one would like a three-dimensional capability, but it is more realistic for now to think in terms of one and two dimensions. Such methods should be unconditionally stable as regards the time differencing of the equation of transfer, must be capable of producing numerical results with a vanishingly small truncation error in the limit of small cells, and must give a qualitatively correct result (the diffusion limit) for large cells.

In this regard, it is recognized that both parallel processing and vector computers are on the horizon, and research is needed as to how the equations of radiation hydrodynamics, in their numerical form, can best be structured to take advantage of these advances in computing technology. A final area of need relevant to this subfield of fluid dynamics concerns the basic data problem. Because of the high temperatures and pressures inherent in radiation hydrodynamics problems, very little relevant equation-of-state and opacity data can be obtained in the laboratory. Thus, continued development is required to improve our theoretical models and calculational techniques for these basic data. Included in this is the increasingly important need for local thermodynamic equilibrium (non-LTE) calculational methods, in which opacities are based on the solution of rate equations describing the population levels of the various states of the atom, rather than on a simple thermodynamic formulation.

Given the proper support and environment, many important advances can be made in the coming years to enhance our understanding and calculational ability of radiation hydrodynamic phenomena. This will be an intellectually stimulating development process, cutting across many disciplines and yielding results that have practical significance in several important national endeavors.

#### POROUS MEDIA

With the current interest in oil exploration, the various phenomena that are associated with the flow of matter and energy through porous media are receiving an increasing amount of attention from the fluid-mechanics community.

In general, single-phase flows can be described by Darcy's law, according to which the velocity is proportional to the pressure gradient. The magnitude of the coefficient of proportionality is, however, unknown as is its dependence on the various properties of the porous material, for example, the void fraction, the tortuosity of the interstices, and the particle size distribution. Several attempts have there-

fore been made to develop a theory for estimating the permeability, and recent results using percolation theory appear promising.

In the case of single-phase porous media flows in soil mechanics and soil hydraulics, additional complications arise that require that the permeability be assumed anisotropic as well as a nonlinear function of porosity and pressure. Environmental problems include wind, water and sea erosion, the permeation of soil by seawater, and land reclamation through irrigation. Important biological porous media flows include the interstitial fluid flow in the articular cartilage, the drainage of intraocular fluid in the eye, blood perfusion in living tissue, and other applications that are mentioned in the section on Biofluid Dynamics.

From a practical point of view, however, the subject of multiphase flow through porous media is an even more important one, especially as concerns oil exploration, but here a reliable theoretical framework (i.e., an extension to multiphase flow of Darcy's law) for modeling the various phenomena is lacking. For example, little is known quantitatively about the dynamics of oil ganglia during immiscible displacement in water-wet porous media, and many fundamental questions that are associated with secondary and tertiary oil recovery remain very much unanswered. The very complicated simulation models that are currently being used in industry are therefore based on a very incomplete knowledge of the physics underlying the various processes.

#### ROTATING PHENOMENA

In this class we place those flows in which Coriolis forces and radial accelerations due to large-scale rotation introduce phenomena not present in flows naturally referable to inertial coordinates.

##### *Turbomachinery Flows*

Strong rotation is an essential feature of turbomachinery flows, as it is necessary to the angular momentum exchange that provides the energy transfer in these ubiquitous devices. The resulting radial pressure gradients and Coriolis forces play essential roles in the behavior of the viscous three-dimensional flows that limit the energy exchange and efficiency. Owing to their great complexity these phenomena have been understood only superficially. With rapidly evolving computational and experimental capabilities, however, these flows will soon become tractable, giving us the possibility of much more rational and effective designs. The potential for energy savings is enormous.

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*The Circulation of the Atmosphere and Oceans*

Motions of the atmosphere and oceans at scales greater than a few kilometers, and time scales greater than a day, feel the Earth's rotation strongly. The Coriolis force and pressure gradient are the dominant forces in both ocean currents and weather systems. Modern computers, theory, and modern field observations are combining to give us, for the first time, a complete dynamical picture of these circulations. Planetary rotation puts severe constraints on the flow, for example, limiting the heat flux from equator to poles and shaping the great wind-driven gyres that fill the upper kilometer of the oceans. The problems of climate change and weather prediction, pollution, and the chemical evolution of Earth and the planets all involve the dynamics of rapidly rotating fields.

With planetary rotation, small-scale fronts and turbulent boundary layers provide a particular challenge, both as fundamental nonlinear dynamics problems and as bottlenecks to the understanding of the large-scale flows. Coriolis forces give weather systems their distinctive nature, which involves elements of Rossby wave propagation, instability, and geostrophic turbulence. The determination of the general circulation of oceans and atmospheres rests on theory and observation of these energetic elements, and the calculation of their back interaction on the mean flow.

## PHASE CHANGE

Phase change is an important element of both natural and industrial processes.

*Technological Applications*

Phase change between liquid and solid states is important to a range of practical problems, for example, energy storage devices, shipment of natural gas and oil through pipelines in cold latitudes, cryosurgical problems like the freezing of living tissue with blood perfusion, storage of blood with cryopreservation, metal cutting and dendrite formation, crystallization, and plating phenomena.

Classical fluid-mechanics techniques like stability theory are being applied, for example, instability theory to model the formation of dendrites in a supersaturated salt solution. The geometric aspects of these problems are often complex, but the range of valuable applications is large. Phase change with irregular boundaries is being modeled

for the case of metal castings. In the complementary case of laser metal cutting, the problem is to model melting around a moving heat source.

In the case of phase-change energy storage devices, one is faced with a difficult free-convection problem in complex geometry.

Cryosurgery as a modality in the treatment of tumors has received considerable attention in the past decade as has the cryopreservation of blood and other living tissue. This freezing is complicated by the nonuniform vascular geometry and regional blood flow in living tissue and solute concentration effects at the cellular level.

Pipe flows may experience phase change if cooled from the exterior; viscous heat generation begins to compete with exterior cooling once the aperture has been reduced. If the pipe is embedded in frozen tundra, the prediction of the melting and ice front in the exterior region must be carried out in parallel.

#### *Nonequilibrium Evaporation and Condensation*

Nonequilibrium condensation and evaporation phenomena have long been of interest in high-speed fluid mechanics. The fluid mechanics of strongly vaporizing or condensing surfaces and the nonequilibrium statistical mechanics of the homogeneous formation of clusters of "multimers" have been studied in the last decade. Both phenomena have numerous potential applications in a variety of industrial processes and in understanding natural events.

In the coming decade it is expected that investigations of cluster formation, and more generally nucleation in supersaturated vapor flow, will provide insights into these important problems, which are at present not well understood. These studies appear to be most successful when done in gas-flow situations, where it is relatively easy to obtain arbitrary degrees of supersaturation. For example, recent results on the probability of occurrence of numbers of molecules in a cluster provide an indication of the cluster's topology or packing scheme. Heterogeneous nucleation phenomena are also extremely important and difficult to describe. It is to be expected that research on homogeneous nucleation will lead to a better understanding of the heterogeneous problems.

A related subject is bubble formation, both heterogeneous and homogeneous, which enters into many practical situations. Boiling heat transfer and cavitation are two examples. This area presents a wide range of problems that will continue to be of interest.

*Geophysical Flows*

Changes of phase of water are at the heart of weather—and climate dynamics. Evaporation at the sea surface and recondensation in tropical cumulus clouds provide the principal motive force for the atmospheric circulation. The evaporation stage involves complex dependence on humidity, wind, and sea state. The process is embedded in turbulent boundary layers both above and below the sea surface. The condensation of water vapor into clouds requires condensation nuclei, and there is a complex of surface chemistry and particle kinetics that interacts with the fluid dynamics of the convecting cloud. Beyond the dramatic examples of these heat engines, like hurricanes, the dynamics of tropical cloud clusters is a central problem in atmospheric dynamics. Parameterization of cloudiness and precipitation in numerical models of the circulation is a significant unsolved problem. Successful three-dimensional simulations of rudimentary, individual convecting clouds are now being carried out; they require the fastest available vector computers.

Sea-ice and terrestrial ice and snow cover affect the dynamics of climate most directly. Floating ice is a complex material, and its growth, movement under wind stress, and fracture are difficult to predict. Freezing produces heavy, saline water, which is a primary cause of deep convection in the high-latitude seas. Once developed sea ice insulates the ocean from further heat or moisture flux. Large-scale models of ice dynamics are beginning to reproduce these effects, while small-scale experiments and observations have clarified the process by which seawater freezes and drains itself of brine.

On land, the hydrologic cycle is a fluid-dynamical problem involving phase change and flow through a complex porous medium. As with the ocean, the groundwater and snow cover act as a memory for climate evolution and long-range weather predictions.

**Topical Subject Areas****AERODYNAMICS**

New theoretical understanding through asymptotic methods, the addition of numerical simulation to theory as an investigative methodology, the use of computers in data acquisition and analysis, and a better understanding of the physics of turbulent processes has accelerated the pace of accomplishment in aerodynamics. Inspired by these intellectual advances as well as by pressing needs, significant contri-

butions have been made to the efficiency of commercial air transports, the performance of helicopters, manned re-entry vehicles, and the effectiveness of military aircraft and weapons systems. One of the principal ingredients to these advances has been the use of the computer as a numerical simulator to aid and abet the understanding of high-speed flows, to assist in data analysis, and as a design tool. Another has been the extension of asymptotic analyses to provide an understanding of the rich physics of flows, such as those about a wing's trailing edge that sets its circulation and determines its lift. A third ingredient has also been realized and has already seen application in flows such as those about helicopter rotor blades. Important recent advances include the development of efficient aerodynamic algorithms for simulating the flow about aircraft, detailed understanding of how viscous and inviscid flows interact, the aerodynamics of supercritical flows, and the utilization of shock-free flows once deemed physically unrealizable.

There are manifold opportunities for major advances in high-speed flows that will extend the developments of the past decade. These past developments have been focused in three primary technological areas: the development of highly efficient commercial and military transports, the development of highly maneuverable fighter aircraft, and the turbomachinery of aircraft engines. These developments will continue primarily from advances in our understanding of separated and unsteady flows, from our special knowledge of new aerodynamic design procedures, from our beginning understanding of and thereby our ability to model and perhaps control, turbulence, and from the continuing growth in the use of computers to simulate aerodynamic flow fields. In many flows of technological interest the flow is either separated or unsteady or both. We are beginning to understand the fundamental physics of these separated and unsteady flows and how, often in combination, they can be used to improve the efficiency and performance of technological devices.

It has been known for some time that the aerodynamic designs that operate at high subsonic Mach numbers are most efficient if they can avoid the generation of shock waves. But such flows are isolated from one another and were originally thought to be impractical. It has been demonstrated over the last decade that these mathematically isolated solutions are of practical value, and special techniques have been developed to find them. These techniques have now been generalized to the point where they can be used routinely in the design process guaranteeing that the extremes of the transonic design envelope can be reached.



TABLE 2.3 Aerodynamics (High-Speed Flows)

Past But Still Recent Advances	Technological Applications	Areas of Rapid Advance and Opportunity	Impediments to Progress	Foreign Competition
Aerodynamic algorithms (e.g., operator factorization)	Aircraft design in all speed ranges	Euler and Reynolds average simulation adaptive grids	Inadequate access of universities to supercomputers (including NAS)	Europe ahead of us in application of fundamental advances in CFD and turbulence
Inviscid-viscous interactions (asymptotics)	Airfoil, wing, and compressor design	Inviscid-viscous interactions	Inadequate basic research funding	
Panel methods (linear theory, CFD)	Subsonic and supersonic design	Turbulent drag reduction		
Real gas effects (reaction rates, CFD)	Shuttle and missile re-entry	Direct simulation of turbulent flows	Industrial lag in applying new results	
Separated flows (understanding, CFD)	planetary re-entry	Vortex flows	Separating numerical from real physics	Europe equally able to distinguish real from numerical physics
Supercritical aerodynamics (theory, CFD)	Efficient wings maneuvering aircraft	Unsteady flows		Soviet Union strong in theory, weak in CFD
	Commercial and military aircraft efficiency			

Transition and turbulence (theory, experiment) Unsteady flows (understanding, experiment, CFD) Vortex lift (understanding, experiment, CFD) Instrumentation	Aircraft performance, especially drag Helicopter rotors, maneuvering military aircraft Supersonic aircraft, helicopters	Control of turbulence or transition Separated flows—3-D and unsteady	
	Acquisition and analysis of flow-field details	Instrumentation, diagnostics, data analysis, and display	Obsolete and expensive to operate facilities
Vector computers, supercomputers	Computational aerodynamics	Smart wind tunnels	Computer CPU size, researcher access
National Transonic Facility	High Re simulation	Transonic testing	
			Many European facilities newer and better
			Soviet Union lacks such facilities. Japan is catching up in supercomputers
			U.S. leads this technology

By the end of the century we may achieve another doubling of the fuel economy of the present-day transport aircraft. This doubling will occur through a number of design innovations in the aerodynamics of high-speed flows, both external to the craft and through its engines. Aerodynamics will contribute significantly to this improvement. For this reason alone, the fundamental physics of these flows is especially important. In addition, there are many devices whose designs may be altered radically if one turns from steady attached flows to unsteady separated flows to improve their performance. Our understanding of the physics of these unsteady separated flows is just beginning and is especially important.

It is clear that in some areas the Europeans are catching up with us in the application of fundamental advances in computational fluid dynamics (CFD) and turbulence. Some believe that they will soon achieve parity in distinguishing real physics from numerical physics, and that they are more rapidly capitalizing on the availability of supercomputers than we are. On the other hand, it is clear that the Soviet Union, while relatively strong in theory, is weak in CFD. While many European facilities are newer and better than ours, generally these facilities derive from ideas that were first implemented in the United States.

The principal bottlenecks to rapid progress in aerodynamics are the inadequate university access to supercomputers, current limitations in computer CPU size, the inadequate funding of university research, the obsolescence and cost of some of our experimental facilities, and the lack of an understanding of transition and turbulence. Research funding needs to address all three elements of the trilogy that comprises analysis (theory), experiment, and numerical simulation.

Table 2.3 delineates past, but still recent, advances, their technological applications, areas of rapid advance and opportunities, the impediments to progress in some of these areas, and the status of foreign competition where appropriate.

We are now beginning to understand better the fundamental physics of the process of transition to turbulence, and through that understanding we are beginning to develop methods to suppress this transition and even turbulence. These controls range all the way from acoustic input to the boundary layer through the removal of a substantial portion of boundary layer from the surface.

## BIOFLUID DYNAMICS

In the past decade, biofluid-dynamics research has undergone an unparalleled growth that has touched on our understanding of nearly every aspect of human, animal, and plant function where fluid-mechanical flows and forces play a significant role. A very positive climate for interdisciplinary research and mutual dependence and acceptance has evolved since the late 1960s between researchers in the biological and medical sciences on the one hand and the physical sciences and engineering on the other. We shall briefly summarize here a few major areas of activity where either significant advances have been made in the recent past or a major development of new ideas is in progress. What earmarks all of these problem areas is that the mathematical models or laboratory model experiments constructed to explain the phenomena are much more closely linked to biological reality than in the past because of close collaborations that have gradually developed with biological and medical researchers.

The study of the flight of birds and insects, the swimming of fish and mammals, and the locomotion of microorganisms has been a constantly expanding interest of fluid mechanicians over the last half century. In the past 10 years, new insights have been obtained into the flight formations of birds, the wave skimming of seabirds, the hovering aerodynamics of bees and hummingbirds, the efficient swimming of large fish such as the tuna, and the flagellar and ciliated propulsion of numerous microorganisms from the cholera-causing bacteria *Vibrio comma* to the mucociliary motion of an egg cell in an oviduct. Theory and elegant validating experiments have been performed to explain the progressive metachronal wave motion of cilia and the mechanism of mucociliary pumping that are vital in the reproductive organs and the bronchial and tracheal air passages. Most recent studies suggest that the rheological properties of mucous may have a profound effect on the swimming of sperm and that more basic studies of the microstructure of this fluid are needed. The effect of thermally induced motions on the swimming of mammals and large fish is another new area of considerable interest.

A problem area that has attracted widespread interest in the past decade is the fluid-dynamic aspects of arterial disease. There is a growing body of evidence that strongly suggests that the small population of endothelial cells (inner cellular lining of blood vessels) involved in turnover (cell death and replacement) at any given time can produce large changes in the permeability properties of the artery wall to lipoproteins and that these changes induced by fluid shearing

stresses may be an important initiating factor in arterial disease. Experiments have been conducted and a microhydrodynamic theory proposed to understand the vesicular transport of cholesterol and other large molecules across the endothelial lining and the effect of fluid stresses on endothelial cell function both in tissue culture and in vivo. Sophisticated numerical and laboratory models of the larger vessels have been constructed to ascertain the stress distribution in vivo, and these models have been correlated with the known predilection sites for atheromatous lesions observed in animal experiments and autopsy.

Cardiovascular fluid mechanics and the rheological properties of flowing blood have been a traditional area of study for biofluid mechanicians. Much of the previous research in this area examined the arterial tree as a branching, nonuniform transmission line for the propagation and attenuation of the pulse pressure or studied the non-Newtonian flow properties of blood. In the past decade, new avenues of research have been initiated on the fluid mechanics of the highly compliant and collapsible veins, on the motion of the deformable cellular components of blood in the microcirculation, and on a more realistic numerical modeling of the ventricular action of the heart. Several new phenomena have been discovered in the nonlinear response of a collapsible tube under steady and unsteady flow conditions as a model for certain flow phenomena in the venous and bronchial trees. Similarly, intriguing new behavior such as the tank treading of a red cell membrane in a shear flow have been observed and explained in microcirculatory flows. Other microcirculatory flow phenomena, e.g., the hematocrit defect in an entire capillary bed, still have no satisfactory explanation.

There are a number of important phenomena in which biological tissue behaves as a porous medium. Prominent examples include the movement of interstitial water and solute diffusion in loaded articular cartilage, the filtration of blood plasma across the walls of the blood vessels, the drainage of interstitial fluid in the lymphatic circulation, the hydration of the cornea, and the drainage of aqueous humor from the anterior chamber of the eye. In all of these problems one is examining the consolidation of a biological porous matrix under pressure loading coupled with biochemical-physical phenomena. A different type of two-phase flow problem is encountered in bioheat transfer theory. Here one would like to determine how the local heat-transfer characteristics of tissue are affected by the blood flow.

An especially fertile area for future research is cellular and microhydrodynamic transport processes. These problems are frequently complicated by the presence of electrostatic, electrodynamic,

and chemical forces. Linear stability theory has been applied to the cell membrane modeled as a viscous fluid layer subject to a perturbation in molecular forces at its surface. Important cellular transport processes currently under study and of great interest to cell biologists are endocytosis, exocytosis, and vesicular transport. The movement of molecules at the entrance to and their passage through the intercellular channels between adjacent cells in a cell layer provides the hydrodynamic basis for both the microstructure of osmosis and the phenomenological coefficients universally used by the biological scientists in describing their membrane transport experiments. The transport of water, small ions, and proteins occurs at discrete locations in a cell layer and not uniformly across the entire membrane surface, as is the case for gaseous molecules. The consequences of this behavior for the transport in the underlying tissue are just starting to be explored.

In the lung the flows of gas, blood, and water are of equal importance, and they take place in an organ that is very flexible. The blood vessels and the alveoli go through large deformations in normal lung function. The oxygenation of blood and removal of  $\text{CO}_2$  relies on the participation of a number of enzymes, which greatly facilitates the mass transport. The flow of water into the lymph or alveoli determines whether one has edema or not. The structural basis (ultrastructure, molecular biology) of the capillary blood vessel wall determines the health or disease of the blood. Thus, in order to understand ventilation and perfusion, fluid dynamics has to be coupled with nonlinear finite elasticity and biochemistry. There has been significant progress made in the past decade, but a detailed quantitative understanding awaits the future.

This brief summary has omitted many fascinating problems involving specialized organs such as the eye, ear, urinary and gastrointestinal systems, and the placenta, where there continue to be many research opportunities for the fluid mechanician. We have also focused on basic physiological processes and have not mentioned the wide range of new medical devices, instruments, or prostheses that have been introduced or the major advances that have been made in the design of artificial organs through the application of fluid-dynamic principles. The search for new noninvasive techniques for measuring local blood flow for clinical diagnosis continues.

#### FLOWS OF ELECTRICALLY CONDUCTING FLUIDS

By interaction with magnetic fields, either self-induced or imposed, electrical conductivity introduces body forces and energy coupling to

the bulk fluid, resulting in a complex of phenomena not present in the classical fluids described by the Navier-Stokes equations. These range from pure magnetohydrodynamic phenomena such as Alfvén waves and forward propagation of viscous wakes to the more complex category involving thermal and ionization phenomena, such as the ionization or electrothermal instabilities in nonequilibrium plasmas.

Studies of these complex phenomena have provided explanations for the behavior of the Earth's core, for events in the Sun's corona. The continued study of magnetohydrodynamics is essential to future progress in these areas, and in cosmology.

Potential engineering applications of magnetohydrodynamics (MHD) include fusion power, electric circuit breakers, electric space propulsion devices, manipulation of molten metals, and MHD power generation. Fusion is addressed at length elsewhere in this report. After a very intensive effort over the last 20 years, funding for electric propulsion and MHD power generation is currently at a low level. Yet many important phenomena remain partially explored or perhaps undiscovered. It is important to continue fundamental work in this area, which, quite apart from its intellectual challenge, may have additional important applications in the future.

#### GEOPHYSICAL FLUID DYNAMICS

The fluid dynamics of the natural world encompasses a vast range of physical phenomena, from atmospheric and oceanic dynamics and climate change to geological processes in the Earth's mantle and core. The subject has evolved naturally to consider the atmospheres of the planets and fluid phenomena in astrophysics.

What makes the geophysical fluid dynamics (GFD) of the atmosphere and oceans challenging is the ten decades of scale between the motions of planetary scale and the motions of smallest scale, where molecular diffusion is important. Thus a theory or computer simulation of the weather must somehow incorporate the cumulative effect of all the smaller-scale fluid dynamics: internal waves, fronts, two- and three-dimensional turbulence, and convective clouds. Intense studies of these intermediate scales of motion are being pursued, for example, with much progress on severe storms, cloud modeling, and frontal dynamics being evident.

A simulation of climatic change must in addition accurately account for the many years of weather, whatever its cumulative effect may be. A theory of the ocean circulation, on the other hand, must cope with its vastly slower response to a change in atmospheric winds or heating. It

must account also for the differing behavior of salinity and temperature, both of which influence the fluid buoyancy. At high latitude the dynamics is made complex by sea ice. The oceans act as a flywheel in the climate system with a time scale as great as a thousand years. The worldwide disruption of weather by the 1982-1983 El Niño event in the tropical Pacific Ocean shows us the powerfully interactive nature of the oceans and atmosphere. Wave-propagation theories have successfully described several of the links in the sequence of tropical and global change.

Beyond these short-term events we are soon to experience the global effect of increasing carbon dioxide in the atmosphere. The prediction of climate change over the next half-century relies on complex fluid-dynamical modeling of the general circulation and its heat and moisture balances. These important problems involve, in addition to classical fluid dynamics, interactions with chemistry (for example, of aerosols in the atmosphere and carbon in the oceans), radiative effects, multiphase and multicomponent fluids (as in convective clouds and in sea ice), and biology. (The biosphere interacts with the fluid atmosphere and oceans in many ways.) Such interactions are crucially important in the possible aftermath of nuclear war, in which the particulate load of the atmosphere may be great and the Sun obscured for months or years.

A promising branch of study in this area is Lagrangian fluid dynamics, in which theory and measurements are carried out using the moving fluid particles as a reference.

We are seeing rapid progress in the understanding of the oceanic general circulation, both the mechanical response to the stress exerted by the winds overhead and the thermodynamical response to heat flux and moisture flux between the air and sea. The complexity of the system would defy any brute-force solution by computer simulation, but there is much optimism that new techniques will lead to a solution: first, radically new measurements of the atmosphere and oceans are now possible using microelectronics, remote sensing (especially from orbiting satellites), and computer analysis, and, second, simple theoretical models of the circulation are emerging that help to reduce the apparent complexity of the system. These theories of the circulations, wave propagation, turbulent cascades, and the induction of mean circulation by eddy motions are laying the groundwork for the coupled model of the ocean-atmosphere system. The close interaction of theory, observation, and computer and laboratory experiment are characteristic of the work.

The study of the atmosphere of other planets has a close connection with GFD: while many new physical and chemical effects are present



on the planets, some remarkable tentative similarities have been found with terrestrial flows. Beyond their own intrinsic interest, the value of studying the other planets is to better understand our own. Intense, isolated vortices, for example, have been observed in Jupiter's circulation; models of them have aided in understanding terrestrial flow, from small severe storms to the intense eddies cast off from the Gulf Stream. Terrestrial general circulation models have been able to simulate some of the banded flows of the outer planets, simply by altering appropriately their planetary rotation and density stratification.

#### MULTIPHASE FLOWS

The analysis of flows in which more than one phase is involved (multiphase flows) offers problems of far more complexity than are encountered with single-phase flows. The reason for this is that the different phases, in general, are not uniformly mixed, and a detailed understanding of how these phases are distributed in a flow field is needed. The importance of these flows can be realized by considering a few examples:

- The transport of crude oil in a pipe usually involves the flow of both liquid and gaseous hydrocarbons. In horizontal pipes at low gas and liquid velocities a stratified configuration is attained whereby the liquid flows along the bottom of the pipe and the gas concurrently with it. Increases in the liquid velocity or a change of orientation to an upward inclination can give rise to a situation where the gas and liquid flow intermittently, thereby creating large pressure pulses, which in turn can cause vibrational damage. Thus, it is usually desirable to design so as to avoid slugging, but, unfortunately, currently available scaling laws are unable to predict either the conditions under which slugs will appear or their properties.

- Another example is found in nuclear reactors, which typically employ water to remove the heat generated by the nuclear decay. A two-phase flow of vapor and liquid occurs in the cooling passages because of the boiling of the liquid. The flow character can vary from a bubbly flow, which consists of a mixture of vapor bubbles and liquid, to an annular flow, whereby a mixture of vapor and liquid droplets flow concurrently with a liquid film on the wall. It is critically important to design these cooling systems so that the wall film does not dry out, because under these circumstances the cooling is insufficient and a runaway reaction can occur.

- As a final example, we mention the transportation of solids, such as coal, in a slurry in a pipeline. Here one of the chief engineering considerations is to avoid settling of the particles, which is accomplished by selecting a proper size range for the particles and a judicious pipeline design. In a long straight pipeline the particles settle because of gravitational forces; this is opposed by turbulence and other hydrodynamic effects, in a manner that is not yet understood. Further basic research on these hydrodynamic effects is needed to provide a solid theoretical basis for the design of slurry pipelines.

In fact, it is not an exaggeration to claim that almost every aspect of a manufacturing facility in the chemical process industry is confronted with multiphase problems. This can involve the contacting of gases and liquids or of solids and liquids, the design of condensers and boilers, the evolution of gas in a chemical reaction, the design of pressure relief valves, or the separation of phases. Quite often the failure of a process design (usually at great cost) can be traced to a poor understanding of the consequences of a scaleup of some part of the system involving a multiphase flow. The recognition of this problem has led large companies to identify critical parts of the flow system and to do full-scale tests to ensure a safe process design.

The problem of scaling multiphase problems can be illustrated by considering the prediction of pressure drop in a long straight pipe. Here, in contrast to single-phase flows where reliable correlations exist that do not require detailed knowledge of the turbulent flow field, in multiphase flows there are so many independent variables defining the system that dimensional analysis leads to too many dimensionless groups to be of use. Consequently, in multiphase flows one has to have a detailed model of the physics of flow in order to correlate test results in a meaningful way.

Current design methods, given in engineering handbooks, usually involve the modification of single-phase relations by using fluid properties that are some combination of the properties of the different phases, an approach the inadequacy of which has been recognized for 25 years. It is quite clear that predictive methods for pressure drop must be tailored to the flow configuration that is expected to exist.

Research in this area has three main aspects: (1) basic studies of multiphase phenomena, (2) the prediction of how the phases distribute for different flows, and (3) the development of design equations as well as computer codes for predicting the distribution of phases in complex flow situations. Basic studies would involve such issues as the mechanism by which particles are entrained and moved by turbulence in a

flowing gas stream or the mechanism by which waves are generated by air flowing over a liquid film. The second aspect of this research involves the use of diagnostic tools to determine how the phases distribute in a particular flow and the use of basic studies to provide an explanation of the observed distribution. The final aspect of research on multiphase flows is the development of design equations and computer codes to predict phase distribution. To date, it has become customary to consider separate differential equations for each phase and to use these as the basis for the computations. Unfortunately, it is quite likely that this aspect of research on multiphase flows is dangerously ahead of our basic knowledge.

### Technical Disciplines

#### MODELING AND ANALYTICAL METHODS

Phenomena found in the natural world and in the industrial environment are identified and described in physical terms. This physical description must then be expressed mathematically in nondimensional form. This delineates the dominant physical mechanisms. These equations are then solved by asymptotic or analytical methods or by numerical means. This process includes the development of physically viable conceptual models based on a synthesis of available data, the generation of rationally derived governing equations and the corresponding and initial boundary conditions, and the development of solutions to quantify the physical process of interest.

All Newtonian fluid-physics processes are described ultimately by a suitably generalized set of Navier-Stokes equations in which chemical effects and radiative transfer may be included. Suitable analogs are developed for non-Newtonian fluids. Unless the solution process is to be based on numerical simulation of the complete general equations, rational approximation schemes are needed to reduce the full mathematical system to a simpler form compatible with the physical model. Significant parameter groups are identified and then employed to develop asymptotic representations of the complete equations. Methods of this genre have permitted an enormous improvement in the understanding of classical ad hoc approximations (for example, boundary-layer theory and potential flow theory) and facilitated the development of techniques for describing very complex flows including, for example, multiple-deck descriptions of trailing-edge flows, shock/boundary-layer interactions, and delta-wing aerodynamics. In fact, major processes in every branch described in this chapter, with the

notable exception of turbulence phenomena, can be attributed to the use of contemporary rational approximation methods.

Once a reduced equation system has been specified, a method for their solution must be found. One can employ exact analytical methods, asymptotic analytical methods, computational techniques, and even formal mathematical methods to find solutions as well as solution bounds, properties, and uniqueness. For most fluid-physics processes useful exact analytical solutions are seldom found. Asymptotic solutions provide a quantitative description of the physical phenomena for limited ranges of parameter values. In highly nonlinear problems (for example, chemically active systems) novel perturbation techniques are needed to find concise, uniformly valid expansion-based solutions. This is particularly important in systems with disparate time and length scales.

Numerical simulation must include assessments of accuracy and resolution so that physically viable solutions are discriminated from those that represent numerical artifacts. Analytically derived asymptotic solutions are not only useful as benchmarks to test numerical methods but also in providing the numerical time and length scales essential in resolving real physics. The need to benchmark numerical simulations is especially important when the numerical model employs the full equations describing the processes involved. In this case, the ensemble of physical processes occurring concurrently is large and the resolution of disparate length and time-scale processes is essential.

Only in the area of turbulence is the mathematical modeling hindered by the lack of definitive conceptual models. Averaged equations derived from the Navier-Stokes equations always have undefined terms that are only described in terms of ad hoc closure approximations. So far, mathematical methods have not yielded rationally derived rules for closure, and a more focused effort toward providing better answers to this question may prove fruitful.

#### COMPUTATIONAL FLUID DYNAMICS

In recent years rapid progress has been made in computational fluid dynamics. The moving force for this development was largely provided by the availability of reliable and powerful computer resources. This in turn has stimulated both theoretical and experimental research toward the understanding of fundamental processes in fluid dynamics. As a result, we currently have the capability to calculate many complex unsteady two-dimensional and steady three-dimensional flows—including the effects of compressibility and viscosity—that were impos-

sible or impractical only a few years ago. There are, however, many limitations that must still be overcome.

Computational aerodynamics has progressed during the last two decades from linear theory for slender-body-flow calculations to nonlinear inviscid theory for flows about aircraftlike configurations. During the last decade there has been much activity in calculating three-dimensional compressible viscous flows past relatively simple aerodynamic shapes using the Reynolds-averaged Navier-Stokes equations with turbulence modeling. These calculations, representing the present stage of development, require only the space-time resolution of the gross turbulence effects and leave the representation of the remaining, although highly significant, turbulence effects to realistic modeling. The computer storage and speed requirements of this stage are much less than those of the next and final stage, which represents by mesh and time-step resolution all sizes of the significant energy-bearing turbulent eddies. With the present and very near future advances in computer technology and numerical method development, we are now on the threshold of extending the Reynolds-averaged calculations to full aircraft at flight conditions. To pass over this threshold into the practical use of such calculations for aircraft design requires the solution of several topological problems in fitting a system of mesh points about a geometric shape as complex as an aircraft configuration, the development of convergence acceleration procedures to enhance the efficiency of numerical methods for solving the equations of compressible viscous flow, and the implementation of solution-adaptive grid systems.

Much progress is also required before the currently available turbulence models will be able to account for the effects of strongly interacting flow fields with moderate or large amounts of separation. There is no assurance that such capability will be forthcoming in the near or even distant future. However, present models can predict to engineering accuracy turbulence boundary-layer interactions with few or no regions of separation. Development of the procedures required to extend viscous flow calculations to complex three-dimensional flows, soon to be possible with forthcoming computers, without waiting for further improvements in turbulence modeling is still a logical next step. These calculations will also be of engineering accuracy for flows near design conditions and can be used to predict incipient separation, shock and vortex boundary-layer interactions, buffet, reduced lift, and interference phenomena. Improvements in turbulence modeling will further extend the range of application, eventually to tactical aircraft in maneuver.

Within the next 2 years computer resources will become available that can process data at a rate of the order  $5 \times 10^8$  floating-point operations per second—two orders of magnitude faster than current machines—with core memories exceeding  $16 \times 10^6$  words. This capability will enable Reynolds-averaged Navier-Stokes calculations to be made about body shapes as complex as modern aircraft at the same cost and time as present calculations for fairly simple geometric shapes. Further improvements in reducing computer cost and time are required to make such calculations practical for aerodynamic design. However, complementary to advances in computer technology, new numerical methods are being developed to increase numerical efficiency. If this research continues at its present rate it is predicted that a fivefold increase in numerical efficiency will occur during the next 5 years and that a possible two-orders-of-magnitude speed increase is projected during the next 15 years for solving the equations of compressible viscous flow.

## EXPERIMENTAL METHODS

### *Instrumentation*

Developments in fluid-dynamic instrumentation techniques over the past 10 years have involved combining extensive computer analysis with well-established techniques, such as conditional sampling of hot-wire probe outputs in the study of turbulence. There has also been an explosive application of laser techniques. For example, we have Raman scattering for rotational temperature, Doppler velocimeters, and excitation techniques (LIF, or laser-induced fluorescence) along with particle and droplet sizing instruments based on laser scattering. These techniques follow the historical trend in gas dynamics and combustion research of striving for ways to measure the energy budgets in fluid flows. The distribution of energy among the classical and quantum-mechanical states of a gas or fluid is fundamental to many areas of fluid-physics research.

The newly developed techniques permit one to investigate flows in ways that have previously not been possible. The drawback of most of them is that they are relatively complicated and time-consuming to use. However, because of a convergence of developments in several fields (medical imaging, large-array processors) it is now possible to anticipate a revolution in fluid-dynamic instrumentation.

The ideal fluid-dynamic instrument is capable of approximately point resolution, is noninvasive, and can obtain data from a relatively large

volume of flow simultaneously and display it in arbitrary planes cut through the volume. Using the computer technology developed for axial tomography in medical imaging combined with single- and multiphoton excitation or scattering techniques in multiangular projection geometry, it is possible to project that with significant support over the next few years many of the characteristics of the ideal fluid-dynamic instrument can be achieved. Note that advances in recent years, say in the identification and study of large-scale structures in turbulent flows, have relied heavily on flow visualization methods including painfully reconstructed information in plane cuts through flows using point-by-point measurements from a few probes. Subsequently, the results are manipulated and displayed by a computer.

Rapid collection of volume data is an essential part of improving wind-tunnel testing efficiencies since only then can full advantage be obtained from introducing on-line computational techniques into experimental studies.

There has been an explosion of instrumentation effort in the atmospheric sciences. Ground-based remote sensing now allows us to measure the turbulence structure of the atmosphere, showing internal waves, turbulence, clouds, severe storms, and jet streams in detail. The impact on theoretical studies has been great, with a new picture of mesoscale structure emerging.

New developments in technology have also led to the development of new oceanographic sensors that drift with the sea motion and are interrogated by satellites. These are expected to provide a wealth of flow information in the next decade.

One area where instrumentation is particularly important and difficult is combustion research. In combustion we seem now to be in a period of active development of experimental techniques. Certain quantities that could not be measured 10 years ago currently can be measured routinely (e.g., rotational temperatures). There are a number of key quantities that cannot be measured routinely but are likely to be measurable routinely in 10 years (e.g., probability-density functions). A large fraction of the progress being made concerns optical techniques.

Optical methods developed during the past 10 years include Raman spectroscopy (of various types) for measuring temperatures and concentrations of various chemical species, Rayleigh scattering for measuring densities, laser-Doppler velocimetry for measuring velocities, resonance fluorescence for measuring radical concentrations, and laser holography for measuring temperature fields. Since combustion envi-

ronments are rather hostile, the remote nature of optical devices can possess importance beyond their obvious nonobtrusive benefits. Capabilities in time and space resolution by optical methods have progressed to a point at which many quantities of interest in turbulent reacting flows can be measured on a space-time resolved basis. Much important knowledge has been obtained in recent years by application of optical techniques to studies of reacting flows in well-equipped laboratories. For example, the nature of the quench layers at the walls for applications in piston engines has been clarified to a large extent by these methods; and contrary to earlier belief, it was established that the wall-quench layer is not a source of unburned hydrocarbons. Progress of this type could not have been made without the new optical methods.

There is still important information that is not fully accessible. For example, the joint probability-density functions for the concentration and the magnitude of the gradient of the concentration (effectively the so-called scalar dissipation rate) in turbulence diffusion flames plays a central role in theories of heat-release rates and of extinction, but no experimental information is yet available. This is just one example of measurement at the frontier of optical techniques in combustion. The results needed are quite likely to be obtained over the next 10 years. There are good prospects for continued improvement in capabilities of the optical methods. Moreover, there are theories in need of testing (and of input parameters) that can benefit from these improvements. Therefore, we can visualize experimental techniques (especially optical techniques) in combustion to be an active area during the next 10 years.

#### *Flow Facilities*

Facilities associated with direct application of fluid mechanics, such as wind tunnels for airplanes, have always been available. The cryogenic wind tunnels for obtaining high Reynolds numbers now being brought into use are a recent example of this historical trend in facility development for aerodynamic purposes. The current efforts to develop an adaptive wall or "smart" transonic wind tunnels is an indication that significant new aerodynamic facilities will come on-line in the next decade.

It is difficult, however, to build significant facilities simply to investigate questions of fluid physics. It seems to us that there may be a need for facilities that are designed for and dedicated to the study of specific areas of the physics of fluid motion. We suggest that the



fluid-physics community be alert to possible needs in this area and, if appropriate, develop open discussion at the national meetings on this subject.

It would be a benefit to fluid physics if unique national experimental facilities could be used on a regular basis by university and other researchers. We are of the opinion that such a program would inject new ideas into the organization operating the facility, as well as permit state-of-the-art experiments by a widened pool of talented researchers. Typically, large national facilities tends to be equipment rich compared with university laboratories. Providing access and attractive arrangements for conducting experiments by visiting investigators may be an efficient way to increase the productivity of these facilities.

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# 3

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## General Plasma Physics

### SCOPE AND OBJECTIVES OF GENERAL PLASMA PHYSICS

Plasma physics is a discipline whose primary concerns are the collective motions of charged particles, electrons and/or ions, subjected to the action of external electric and magnetic fields and to the action of their own self-fields. This assembly of particles and fields represents a fluidlike medium called a plasma. Basic plasma physics is a study of this fluid. In particular, it concerns itself with such questions as plasma equilibrium and stability, confinement, wave-propagation, instabilities, turbulence, and chaos.

We define general plasma physics to include basic plasma concepts and their applications. In this section we have included (with a few exceptions) applications whose main motivation is *not* thermonuclear fusion or space plasmas. These are dealt with in other sections. Here we examine a number of different applications such as free-electron radiation sources, x-ray lasers, plasma isotope separation, and collective and laser-driven accelerators. Much of this work is motivated and supported by defense-related problems.

Application of basic plasma physics to the development of new technologies requires substantial financial support. In this respect we note that the development of plasma physics is largely incidental to the main objectives, and the amount of support for it is also quite ill-defined. Nevertheless, it is imperative to consider basic plasma

physics along with the development of new technology because their future prospects are so strongly coupled.

The 1960s may be regarded as a time in which the linear theory of plasma fluctuations was put on a firm basis. The 1970s saw the development of nonlinear plasma physics: the behavior of large-amplitude waves, including particle trapping, saturation, wave-breaking, and turbulence; the discovery of new nonlinear phenomena such as Langmuir and ion acoustic solitons; ponderomotive effects of intense electric fields; parametric instabilities, which are growing wave-wave interactions; tearing modes that cause magnetic lines of force to become braided or to form magnetic islands. The development and widespread use of computational techniques has provided the missing link between theory and experiment.

The broad-based fundamental studies of the past two decades have solidified the underpinnings of the relatively new science of plasma physics, with the result that the predictive power of plasma theory has been considerably increased, and the occurrence of experimental surprises has become less frequent. For instance, the possibility of driving a dc current in a tokamak with radio-frequency fields was indicated by the theory of wave-particle interactions, and the occurrence of stimulated Brillouin scattering in high-power laser fusion experiments was anticipated by work on parametric instabilities.

What will be the principal directions of progress in the 1980s? Surely the increased power of computers will lead to a deeper understanding of nonlinear phenomena, especially in two and three dimensions. The transition from order to chaos has been an area of activity and progress in nonlinear dynamics, and applications in plasma physics will lead the way in further development of this topic of general physical interest. Important unsolved problems remain to be carried over into the next decade; for instance, the scaling of electron transport in toroidal devices, anomalous heat conduction in laser-produced plasmas, the detailed mechanisms in field-line reconnection, and the formation of charge layers (double layers) in the Earth's magnetic field and in laboratory plasma.

A dedicated study of plasma physics can be expected to lead to exciting new avenues and possibilities. For example, dense nonneutral plasmas of relativistic electrons will become available with new types of accelerators where collective effects dominate. Possibly revolutionary new ion and electron accelerators will contribute to high-energy physics, energy problems, and weapons. New coherent sources of radiation, particularly x-ray lasers, will appear initially for defense problems and then for applications not yet perceived. The growth of

plasma physics in its impact on related sciences and on areas of practical application has not diminished since its birth in the 1950s, and it is reasonable to expect that this growth will continue in the next decade and beyond.

It is unfortunate that support for basic plasma-physics research has practically vanished in the United States. The number of small laboratories engaged in fundamental investigation of plasma behavior is several times larger in Japan and in Western Europe than in the United States, where only a handful of universities are able to derive support for such studies. Continued evolution of our understanding of plasma and discovery of new applications, in the way solid-state physics has continued to develop, for instance, will require a reasonable level of steady support for research that is not mission oriented.

Only National Science Foundation (NSF) support is clearly for this purpose, and a few universities have support—the total budget for basic plasma physics is about \$2 million. The 1970s saw the growth of large machines for fusion studies and defense problems. It was also marked by the decline of basic plasma physics. It was generally believed that because of the large machines and corresponding budgets that a great deal of support was available for basic plasma physics. In fact, the support has almost disappeared, and the activity has been almost completely eliminated. Progress in plasma physics depends on the foundation provided by basic plasma-physics research; if that foundation is not continually strengthened, ultimately the whole field will suffer.

#### INTENSE BEAMS—ELECTRONS, IONS, AND PHOTONS

The development of high-voltage pulsed power systems was initiated in the early 1960s by J. C. Martin at the Atomic Weapons Research Establishment in England. The essential feature of this research was the successful development of techniques for using Marx generator technology to pulse charge a high-speed transmission line in order to produce short-duration 10-100-ns high-power pulses. Since that time the development of pulse power technology has been quite rapid. During the 1960s terawatt ( $10^{12}$  watts) machines were developed, and during the 1970s, tens-of-terawatt machines were built. They were used to produce electron beams, ion beams, and Z-pinch plasmas. The particle beams are of sufficient intensity that the collective self-fields are of decisive importance, which is why the subject has become a part of plasma physics rather than accelerator or particle physics. Initially, the primary purpose was the simulation of nuclear weapons effects,

and research programs were mainly funded by the Department of Defense (Defense Nuclear Agency) and the Department of Energy. During the past 10 years, other applications have developed including light-ion inertial-confinement fusion, compact torus/magnetic-confinement fusion, microwave generation, collective accelerators, laser pumping, and x-ray sources.

The major accomplishments of the past 10 years (up to 1984) are as follows.

#### **Development of Low-Impedance Multiterawatt Machines**

The new generation of pulse power machines includes PITHON (5 TW) at Physics International Company; Blackjack V (10 TW) at Maxwell Laboratories, Inc.; and the Particle Beam Fusion Accelerator (PBFA I) at Sandia National Laboratory (SNL) (20 TW). PBFA II at SNL is currently under construction, with a design power of 100 TW.

#### **Intense Ion Beams**

Intense electron beams (currents up to a few mega-amperes and voltages up to 10 MV) were developed in the 1960s. In the 1970s, a great deal of research was carried out on ion diodes and ion-beam propagation at the Naval Research Laboratories (NRL), SNL, Cornell University, and the University of California, Irvine (UCI). Diodes were developed to be used with existing pulse power machines. Ion beams with ion currents up to about 0.5 MA were obtained with reflex diodes, pinch diodes, and magnetically insulated diodes. In each case both electrons and ions are present in the diode, but the electron motion is inhibited by magnetic or electric fields so that the current is primarily an ion current. For some time both electron and ion beams were considered for inertial confinement fusion; the Electron Beam Fusion Accelerator (EBFA) project was changed to Particle Beam Fusion Accelerator (PBFA) during this period. The survivor was light-ion inertial fusion, and light-ion focused beams achieved a power density of  $10^{12}$  W/cm<sup>2</sup>. Another motivation for ion beams was to make a compact torus configuration with ion rings. Although ion currents as high as 0.7 MA were achieved, this was insufficient for compact torus configurations that require field reversal. It was established that neutralized ion beams could be transported across magnetic field lines, focused, and injected into a tokamak.

### **Development of High-Energy, High-Current Machines**

Pulse power machines based on Marx generators and pulse lines have been limited to about 10 MV. The Advanced Test Accelerator (ATA) was developed and construction completed at Lawrence Livermore National Laboratories (LLNL) in 1983. It is an induction accelerator capable of accelerating 10 kA of electrons to an energy of 50 MV. The successful development of this machine will provide access to electron-beam parameters that should open up new fields and applications. It should have an impact comparable with that of the Marx-generator/pulse-line systems. It is now being used in beam-propagation studies. Designs for using the beam in a high-power free-electron laser configuration operating at infrared frequencies are under way.

### **Z-Pinch X-Ray Sources**

An annular plasma is formed by exploding thin foils or multiple wires or by gas flow through a nozzle and subsequent ionization. A large current is produced in the plasma with a pulse power (up to 5 MA) machine that causes the plasma to implode, reaching densities of  $10^{21}$  electrons/cm<sup>3</sup>. On impact the kinetic energy of the plasma (hundreds of kilojoules) is thermalized and radiated. The observed radiation involves a continuum corresponding to temperatures of 100-1000 eV and K-shell line radiation of typically a few keV according to the plasma composition. The intense soft-x-ray source is of interest for atomic physics of highly stripped ions in plasma and for various applications including lithography, microscopy, and x-ray lasers.

### **Propagation of Charged-Particle Beams in Gas and Plasma**

During the past 15 years there has been a substantial research effort devoted to propagation of relativistic electron beams and high-current ion beams in gas and plasma. This problem is of interest in connection with directed energy weapons as well as with the need to transport and condition beams efficiently for various other applications, including, in particular, heavy-ion and light-ion inertial fusion. Such beams are subject to a variety of instabilities: two-stream and return-current instabilities have been identified as dominant in certain regimes where the plasma density is relatively low, while the hose instability appears to be dominant in cool weakly ionized gas at densities above a few Torr. These instabilities have been studied both theoretically and

experimentally with reasonable agreement reached. In recent years, multiply pulsed electron-beam generators and energies from 5 to 50 MeV have become available. These facilities should open up a variety of far more interesting propagation studies over a wide parameter space; as such they have led to a surge of theoretical development as well. Research interest now centers on such areas as equilibrium and instabilities of beams in self-generated density/conductivity channels, transport processes in the plasma channels (hydro, chemistry, radiation, and collisional processes in partially ionized gases), and optimization of beam parameters for efficient transport. Other applications of intense beams to collective accelerators, laser accelerators, and coherent-radiation sources have developed sufficiently in the last 10 years that they are discussed in separate sections.

#### **Expectations and Recommendations for the Next 10 Years**

The plasma physics encountered in the study of intense beams is mainly determined by the accelerator capability. In considering the next 10 years we need to consider the availability of existing accelerators and new accelerators likely to be developed.

The scaling laws of low-impedance Marx-generator/pulse-line machines are now well understood. It is unlikely that machines larger than Blackjack V or PBFA II will ever be built. Major advances beyond the present state will only take place if new technology is developed. The present trend is toward inductive energy storage and the development of a fast opening switch. A plasma erosion opening switch has been developed at NRL that has been tested on the pulse lines Gamble I (1 MV, 500 kA) and Gamble II (3 MV, 1 MA). Energy was transferred from the pulse lines to an inductor. Then the energy was switched to the load. Pulse compression of a factor of 3 and power multiplication of a factor of 2 were observed—compared with direct coupling from pulse line to load. At present the erosion switch is used to upgrade the performance of large existing accelerators such as Blackjack V and PBFA I. Such switch developments may lead to new machines with much larger power and energy.

Applications of pulse power machines are currently limited because of the deficiencies of the repetition-rate technology. This also depends on the creation of new switches that can survive. Recent advances in magnetic switches have revived interest in this problem, which had been postponed for the past 10 years.

The new area of high energy and high current will be limited to LLNL and LANL unless less-expensive machines can be developed.

(The cost of ATA is about \$50 million or about \$1/volt). High-current betatrons can be modified by adding a toroidal magnetic field to control the space charge. This type of accelerator is being developed at NRL and UCI, and such an accelerator for research purposes should be much less expensive than ATA.

The acquisition of experimental information and the resultant progress in plasma physics proceeds a great deal more slowly than one might expect considering the number of laboratory machines and physicists. As long as new machines are being built, much of the staff are occupied with the task. After the machine is completed the management of the machine takes more staff, but usually the laboratory gets involved in yet a larger machine before completion of the smaller machine. Budget limitations often force the shutdown of a relatively new machine to make the resources available for the larger machine. Budget allocations for machines typically take precedence over anything else. For example, in 1982, SNL received a budget allocation of about \$20 million to build PBFA II and a reduction in operating budget. This is typical of most laboratories except for universities and NRL, which have not built any large machines in recent years. As a result, most of the research has been done at universities and at NRL. Large machines do not advance our knowledge until many years after they are built—after the machine is no longer interesting in itself, it may be used to study intense beams if it has survived the budget axe. For example, Blackjack V has been in operation since 1978 but has never been available for making beams of electrons or ions. Of course, the large machines are not built to learn plasma physics, which is perceived to be at most incidental to the main purpose. In the long run, the basic understanding of plasmas is usually important to the main purpose. If a means could be found to make large machines available for research after the original purpose has been served, it would be a great stimulation.

### COLLECTIVE ACCELERATORS

Collective accelerators make use of the electric and magnetic fields of charged particles in the region of the space where particles are to be accelerated or focused, or both. In principle, very large accelerating and focusing fields are possible, and the fundamental goal is to make use of these large fields to build high-performance accelerators very economically.

During the past 10 years research has been carried out on five different types of ideas.



### Space-Charge Accelerators

Intense relativistic electron beams are used to make a moving potential well to pull ions along with the beam. Accelerating fields typically of 1 MV/cm have been observed over a distance of about 10 cm. The number of ions accelerated is about  $10^{12}$ , and this requires about  $10^{16}$  electrons. In one form of this accelerator called the Luce diode, proton energy as high as 45 MeV was observed. The central problem is control of the motion of the moving potential well. Many ideas were studied, and most of them were shown to be valid in principle but not precise enough to accelerate ions to high energy. The only continuing effort is on the Ionization Front Accelerator at SNL. In this scheme the electron beam propagates through a gas that is not significantly ionized by the beam. Ionization of the gas is accomplished in a controlled way by means of a laser and a series of light pipes; this controls propagation of the electron beam and the motion of the potential well for ions.

### Wave Accelerators

Waves supported by a relativistic electron beam are used to trap and accelerate ions as in a conventional linear accelerator. The waves must have variable phase velocity and should be "negative energy waves" so that ion acceleration that takes energy from the wave will cause the wave to grow rather than damp. A space-charge wave (Cornell University) and an electrostatic electron cyclotron wave (Austin Research Associates) have been studied for this purpose. The space-charge-wave effort continues at Cornell University. There is another related effort at NRL in which an electron beam is chopped into a sequence of rings that pass through a series of short solenoids. The resultant accelerating field resembles that of a wave with controlled phase velocity. It is a wave accelerator, but the wave is not bound by the plasma dispersion relation. This is a continuing effort.

### Electron-Ring Accelerators

The electron-ring accelerator (ERA) was proposed by Soviet physicist V.I. Veksler in 1956. An electron ring is formed in a magnetic mirror, and ions are trapped in it. Acceleration takes place by means of an electric field or changing magnetic field along the ring axis. This is the most extensively investigated collective accelerator. There have been projects at Dubna in the Soviet Union, Lawrence Berkeley

Laboratory, University of Maryland, and Garching in the Federal Republic of Germany. Only the Dubna group is still working on electron-ring accelerators. They reported significant progress in 1978—acceleration of  $5 \times 10^{11}$  nitrogen ions to 4 MeV/nucleon with an electron ring that contained  $10^{13}$  20-MeV electrons.

### Collective Focusing Accelerators

Here, collective fields are used only for focusing, and acceleration is conventional. One form at SNL is called Pulselac. It consists of a series of ion diodes. Electrons are injected to provide charge neutralization and transverse focusing, and transverse magnetic fields prevent electron acceleration. Another form is a cyclic accelerator that is studied at UCI. Electrons are confined in a bumpy torus, and the electrostatic fields focus a smaller number of ions that are accelerated as in a betatron. 3000 A of  $C^+$  ions have been accelerated to 600 keV in Pulselac. Electron confinement in the cyclic accelerator has been documented. Both projects are still active.

The experimental results in almost all of the collective accelerator experiments have demonstrated that the principles are sound. However, the number of ions accelerated and the final energy have not been impressive; in general both have been less than expected initially. The experiments still active, the Ionization Front Accelerator (SNL), space-charge wave accelerators (Cornell, NRL), and collective focusing accelerators (SNL, UCI) will probably give similar results. The question is, "What will happen after the initial research is completed assuming that it is successful?" The next phase in which more interesting particle parameters are reached will surely be much more expensive. The only collective accelerator to date to proceed to the next phase is the ERA in Dubna, where a heavy-ion ERA to reach 20 MeV/nucleon was authorized in 1981. During the past 10 years the level of support was \$2 million to \$3 million/year in the United States. A level of support of about \$5 million/year for research was recommended in a 1981 DOE study. It is also important that about \$10 million be available to convert a successful research effort into a useful accelerator.

### LASER-DRIVEN ACCELERATORS

The availability of high-power laser beams ( $\geq 10^{14}$  W) brings about the possibility of using these high fields to accelerate particles to energies in the tera-electron-volt range and beyond. Using conven-

tional acceleration methods it is difficult to envision particle energies going above a tera-electron volt without an enormous investment in money and real estate. For example, if we assume for conventional accelerator schemes electric field gradients as high as 100 MeV/m, acceleration lengths of about 10 km would be needed to reach tera-electron-volt energies. Such accelerators are in principle feasible; however, the cost may be prohibitive.

The possibility of utilizing the extremely high electric fields associated with laser beams to accelerate charged particles has been under investigation for over two decades. Electric fields associated with intense laser beams can be as high as  $10^9$  V/cm. Direct use of these fields for continuous particle acceleration is of course not possible owing to the transverse polarization and rapid oscillation of the fields. A number of laser-driven acceleration schemes have been suggested that either utilize a small fraction of the laser field for acceleration or use the laser beam or beams to excite a plasma wave, which in turn traps and accelerates charged particles.

Owing to the speculative nature of the various laser-driven acceleration schemes the subject has suffered from a lack of funding. Recently, because of the progress made in understanding the physics and limitations associated with the various schemes, the funding profile appears to be more favorable, at least for the next few years.

The following list gives a brief qualitative description of the various acceleration mechanisms (not necessarily in order of priority) that are considered potentially attractive.

#### **Beat-Wave Accelerator**

This is a collective acceleration scheme that utilizes the enormous self fields of an excited plasma wave. The plasma wave is excited by the parametric coupling of two laser beams having a frequency difference equal to the characteristic plasma frequency. Since the phase velocity of the high-amplitude plasma wave is slightly less than the velocity of light, electrons can be trapped and accelerated by the plasma wave. A potentially attractive variation of the beat-wave accelerator is the Surfatron. In the Surfatron a transverse magnetic field is externally applied, permitting the accelerated particles to  $\mathbf{E} \times \mathbf{B}$  drift in a direction transverse to the laser propagation direction. In this configuration the electrons can remain in phase with the plasma wave, allowing unlimited electron acceleration to take place. Recent experiments at UCLA have demonstrated the principle of wave formation using two high-power lasers.

**Inverse Free-Electron-Laser Accelerator**

In this scheme a particle beam together with an intense laser pulse is propagated through a spatially periodic magnetic field known as a wiggler field. The wiggler period and laser wavelength are such that the transverse particle velocity due to the wiggler field is in phase with the transverse electric field of the laser radiation. By appropriately contouring both the wiggler amplitude and period the injected particles can be continually accelerated. The inverse of this process has been used to generate radiation and is the well-known free-electron-laser mechanism. (See section below on Coherent, Free-Electron Radiation Sources.)

**Grating Accelerator**

When electromagnetic radiation propagates along a diffraction grating a slow electromagnetic surface wave is excited along the grating's surface. This scheme utilizes the slow electromagnetic wave with phase velocity less than the speed of light to trap and accelerate a beam of injected electrons.

**High-Gradient Structures**

This scheme is basically a scaled-down version of a conventional slow-wave accelerator structure. Radiation power sources in the centimeter wavelength range appear appropriate for this approach. The potential advantage of this scheme is that owing to the short wavelength employed, relatively low radiation energy per unit length is needed to fill the small structure, and breakdown field limits appear to be higher.

**Inverse Cerenkov Accelerator**

This approach takes advantage of the fact that the index of refraction of a neutral gas is slightly greater than unity. The laser radiation within the gas has a phase velocity less than the speed of light, making it possible to trap and accelerate an injected beam of particles.

**Cyclotron Resonant Accelerator**

Here an electron beam is injected along a uniform magnetic field together with a parallel propagating laser beam. Because of a self-

resonance effect, the phase of the electron's transverse velocity can be synchronized with the radiation electric field. This synchronism is maintained throughout the acceleration length.

### **Problem Areas**

A number of issues remain to be solved before laser-driven acceleration schemes can become a viable alternative to conventional acceleration mechanisms. Among the most important unsolved problems in this area is that of refocusing of the intense laser beam for multistage acceleration. The laser acceleration schemes mentioned previously are not compatible with single-stage acceleration of particles to tera-electron-volt energy levels. All of these schemes require multistage acceleration even if the ultrahigh field gradients can be achieved. For example, assuming a gradient of  $10^8$  V/cm for a laser-driven accelerator, lengths of 100 m will be required to reach tera-electron-volt energies. However, owing to the diffraction characteristics of radiation beams, refocusing methods will certainly be necessary to maintain a collimated laser beam over these distances. Because of the high intensity of these beams, conventional focusing procedures do not appear to be possible. Possible solutions to this problem may involve plasma self-focusing of laser light or the use of multilayered dielectric-coated laser waveguides.

### **Recommendations for the Next 10 Years**

The subject area remains speculative, and as yet no configuration or scheme can be convincingly shown to be capable of achieving tera-electron-volt particle energies. Recently the DOE increased its support of laser-driven accelerator schemes to a level of \$750,000 per year. This increase comes at an appropriate time in the evolution of this field, since many conceptual schemes have reached a point where serious detailed and costly studies will be required. It is therefore prudent to at least maintain the present funding level. As mentioned, a number of laser-driven accelerator schemes are under serious consideration and will require several years for evaluation. Upon completion of the initial phase (around 1986 or 1987) an advisory group consisting of laser, accelerator, and plasma physicists should be convened to evaluate comprehensively the progress and likelihood of success of the various acceleration schemes. A decision to change the funding profile for the various schemes could be made at this time based on the outcome of the review.

The DOE was and probably will be the primary source of funds for laser-driven accelerator research. DOE funding started in 1976 at a \$100,000 per year level until 1983, at which time it was increased to \$750,000 per year. It is expected that this level will remain fairly constant until around 1986. At that time a major review will take place to decide the future funding profile.

### COHERENT, FREE-ELECTRON RADIATION SOURCES

The possibility of developing lasers and masers in which the active medium is a stream of free electrons has evoked much interest in recent years. The potential advantages are numerous and include continuous frequency tuning through variation of the electron energy, and very high-power operation, since no damage can occur to this lasing medium as can happen in solid, liquid, and gas lasers.

The concept of transforming the kinetic energy of free electrons into coherent electromagnetic radiation is by no means new; as early as 1933, P. Kapitza and P.A.M. Dirac predicted the possibility of stimulated photon scattering by electrons. Indeed, the klystron, the magnetron, and the traveling-wave tube conceived and developed in the 1940s and 1950s are examples of such free-electron sources capable of generating coherent microwave radiation. In the decimeter- and centimeter-wavelength ranges, these devices can be made to emit at power levels as high as tens of megawatts and with good efficiencies exceeding 60 percent. Today these systems, and variations thereof, have become indispensable instruments of modern science, technology, and communication.

The new generation of free-electron radiation sources being actively pursued at many centers aim to extend the electromagnetic spectrum from the microwave to the millimeter, infrared, visible, and ultraviolet regimes with previously unattainable intensities and efficiencies. Potential applications are numerous. They include the following:

(a) *Spectroscopy.* This area involves spectral studies in condensed-matter physics and of atoms, molecules, and ions; isotope separation; surface studies in the presence of absorbed molecular species; dynamics of charged carriers in semiconductors; fast chemical kinetics; and photochemistry.

(b) *Accelerators.* High-power microwave tubes have traditionally been important in the development of radio-frequency (rf) accelerators. The development of high-power, centimeter-wave sources could be of much value for the high-energy-accelerator community. Conventional

rf accelerators use microwave klystrons operating in the vicinity of 25 MW of peak power. Recent developments indicate that the novel sources could operate at hundreds of megawatts or even gigawatts. These higher powers translate into fewer power tubes; the use of centimeter waves could lead to higher average accelerating gradients and therefore shorter accelerators.

(c) *Radar.* Most radar applications have been at microwave frequencies (centimeter waves and longer), owing primarily to the availability of power tubes and components and to the low atmospheric losses at these wavelengths. Since the new sources can operate in the millimeter- and submillimeter-wavelength regions, applications to future radars are possible. Relative to conventional microwave radars operating at millimeter wavelengths the new systems would have narrow beam widths, large bandwidths, and small antennas. Narrow beam widths would, for example, be important in low-elevation-angle tracking. Large bandwidths enhance resistance to electronic countermeasures and permit high resolution. Millimeter waves are less affected by fog, clouds, rain, or smoke than are optical or infrared waves.

(d) *Thermonuclear Fusion.* The problems of plasma heating are still impeding the practical development of magnetic fusion power reactors. The development of high-power sources at millimeter wavelengths could solve some of these problems. Furthermore, there is now good evidence that electromagnetic waves can drive current in tokamaks, thus opening the possibility of initiating current flow (ramp-up) in tokamaks or even steady-state tokamak operation.

In addition to the above, one can perceive applications in biology and medicine, and as is true for all new advances in technology, the ultimate and most important applications have yet to be identified.

The fundamental principle operative in all free-electron radiation sources is electron bunching in the presence of an ambient electromagnetic field. The field can be externally applied, or it may be emitted spontaneously by the accelerating electrons. In a system properly prepared, as for example by judicious phasing of the rf field, the electrons initially distributed at random can be made to form clusters. If the dimensions of the clusters are comparable with or smaller than the wavelength of the desired radiation, each cluster radiates in a coherent manner like a giant electron. The newly produced radiation reinforces the original field, which leads to even tighter clusters, and so on. Thus, the principle of bunching is synonymous with the stimulated emission well known in conventional lasers.

The three most prominent free-electron radiation sources actively studied during the past several years are (a) cyclotron resonance masers (CRM) of which the gyrotron is a typical example; (b) the free-electron laser (FEL); and (c) the relativistic magnetron. Of the three, the gyrotron is by far the most advanced as a practical device and at present offers the most efficient means of generating intense radiation in the centimeter- and millimeter-wavelength ranges. The FEL has great potential of becoming a promising source at submillimeter wavelengths; and the relativistic magnetron has produced unprecedented power levels ( $\sim 1$ -10 GW) at centimeter wavelengths.

The CRM consists of a beam of monoenergetic electrons streaming along and gyrating in an external guiding magnetic field. The emission mechanism is essentially stimulated synchrotron (or cyclotron) radiation. Electron bunching is in the azimuthal direction and leads to the formation of clusters that rotate about the magnetic field lines. The radiation frequency is approximately equal to the electron-cyclotron frequency.

In an FEL a beam of monoenergetic electrons is injected into a spatially periodic magnetic (wiggler) field, which imparts an undulatory motion to the electrons. Here electron bunching is axial, that is, in the direction of electron flow. The wavelength of the radiation is proportional to the wiggler periodicity. The constant of proportionality depends on the speed imparted to the electrons at the gun. For electrons whose velocity is much less than the speed of light, the constant of proportionality is approximately unity. However, when a high-voltage accelerator is used to produce electron speeds that approach the speed of light, the constant of proportionality can be very small compared with unity, and extremely short wavelength radiation can be thereby achieved.

In the relativistic magnetron a relativistic electron stream passes over a periodic assembly of resonators in which electromagnetic radiation is induced and stored. High powers are achieved by using field-emission cathodes to create extremely high current streams. The radiation wavelength is approximately equal to the spacing between resonators.

Some outstanding problems are the following:

(a) *Accelerators.* Novel free-electron radiation sources are characterized by high-voltage (100 kV-100 MV), high-current (10 A-10 kA) electron streams of superior quality (low emittance). Thus, achievements in the field of radiation sources will be closely linked with progress in accelerator technology and beam-production capabilities.



This is particularly true in the case of free-electron lasers, which require accelerators that are at the limits of present-day capabilities. Advanced designs of electron guns and beam-focusing techniques will have to be studied.

(b) *rf Power-Handling Capabilities.* Extremely high levels of electromagnetic radiation require design and development of new millimeter- and submillimeter-wave components including detectors, mirrors, mode converters, attenuators, and spectrum analyzers. Even at low power levels, development of millimeter and submillimeter hardware is urgently needed.

(c) *Mode Control.* At short wavelengths, the electromagnetic modes in millimeter-wave resonators or optical cavities are closely spaced in frequency. Thus the systems may oscillate simultaneously in two or more modes, which leads to loss of efficiency and degradation of spectral purity. Novel ways of mode control will require further study.

(d) *Collective and Nonlinear Phenomena.* At high currents self-fields associated with the electron streams become prominent and affect the radiation growth rate and spectrum. Furthermore, at high radiation levels, nonlinear wave-particle interactions limit the device efficiency. Both problems have been addressed, but further theory and computer simulations will be required in the future.

(e) *Personnel.* The most urgent problem facing progress in the area of electromagnetic sources is the catastrophic lack of qualified physicists and engineers. The generation of outstanding people trained during World War II and their immediate descendants kept the field alive until the late 1950s, at which time enthusiasm diminished. From then on the training of young people virtually ceased. Since the advent of the novel sources in the late 1970s and the importance of rf heating in thermonuclear fusion research, interest has once again been on the increase. However, a crash training program at universities would be necessary for the United States to keep abreast of the research and development in foreign countries.

Funding for research and development in coherent free-electron radiation sources has come primarily from DARPA, ONR, AFOSR, AFSC, and NSF. Between the years 1979 and 1983, the funding level totaled approximately \$24 million. The total projected level for the years 1984-1985 is approximately \$16 million. The overall funding is adequate, but more is needed for basic, university research in this area.

## ELECTROMAGNETIC WAVE-PLASMA INTERACTION

## Scattering and Absorption of Electromagnetic Waves by Plasmas

The advent of powerful lasers has led, in the past 10 years, to the discovery and understanding of nonlinear phenomena occurring when matter is subjected to intense electromagnetic radiation. The efficiency of absorption of laser light sensitively affects the feasibility of inertial confinement fusion, in which pellets containing deuterium-tritium fuel are compressed and heated by laser-driven ablation. In early experiments, energy absorption was found to be lowered by nonlinear processes in the plasma corona, which quickly forms around the solid core of the pellet. Studies of these phenomena both in small-scale experiments and in those involving the largest existing lasers, coupled with extensive numerical simulations, have confirmed many theoretical predictions and have led to the partial control of the deleterious effects, mainly by the use of shorter-wavelength radiation.

Absorption of laser light occurs near the critical layer in the corona, where the plasma frequency  $\omega_p$  is equal to the light frequency  $\omega_0$ . The corresponding plasma density is  $10^{21} \text{ cm}^{-3}$  for  $1.06\text{-}\mu\text{m}$  light from Nd-glass lasers and  $10^{19} \text{ cm}^{-3}$  for  $10.6\text{-}\mu\text{m}$  light from  $\text{CO}_2$  lasers. Three processes can cause absorption: (1) classical collisional absorption, or "inverse bremsstrahlung," (2) resonance absorption, and (3) the parametric decay and oscillating two-stream instabilities. The most benign of these mechanisms is inverse bremsstrahlung, which increases with laser frequency (because the critical density, and hence the collisionality, is increased) and also with density scale length (because a discontinuous density jump would act like a mirror).

Resonance absorption occurs when light is incident at an angle to the plasma normal so that the electric field vector has a component along the density gradient. Plasma waves are then generated at the expense of electromagnetic energy, and the plasma is heated by the damping of these waves. The copious production of superthermal electrons (and of fast ions accelerated by the charge separation electric field) is a dominant feature of long-wavelength experiments, such as with  $\text{CO}_2$  lasers, and makes resonance absorption an undesirable mechanism. The most devastating effect of fast electrons is their ability to penetrate into the solid core of the target and preheat it, thus preventing its compression to the density required for fusion breakeven.

Parametric instabilities involve the unstable decay of light waves, plasma waves, and frequency-shifted light waves. A large step in the theory of these instabilities was made about 10 years ago. Subse-

quently, these phenomena have been detected and verified experimentally, both in basic experiments and in solid-target shots at large laser installations. Parametric instabilities can be classified into critical phenomena occurring at  $n = n_c$  or  $\omega_o = \omega_p$ , quarter-critical phenomena occurring at  $n = n_c/4$  or  $\omega_o = 2\omega_p$ , and underdense phenomena occurring at  $n < n_c/4$  or  $\omega_p < \omega_o/2$ . The first class contains the parametric decay and oscillating two-stream (OTS) instabilities mentioned earlier. The OTS has been seen only in its nonlinear soliton stage, but the former has been studied meticulously in large-scale microwave experiments. In laser experiments there has been little evidence of the importance of these parametric instabilities to absorption.

Phenomena at quarter-critical density include the two-plasmon decay and absolute Raman instabilities. The latter is a limiting case of the stimulated Raman scattering (SRS) instability discussed below; the former is a stronger effect involving the generation of two plasma waves, preferentially at  $45^\circ$  to the laser beam. The main features of the two-plasmon decay instability were confirmed in a basic experiment in which the decay waves were detected by Thomson scattering. This instability also produces fast electrons and is often seen in solid-target experiments from its characteristic signature of scattered light at a frequency  $(3/2)\omega_o$ .

At densities below quarter-critical, the main effects are filamentation and the SRS and stimulated Raman scattering (SRS) instabilities. Filamentation is the tendency for laser light to break into small beams by creating plasma channels with its own ponderomotive force. Though indirect evidence for this is available, there has yet been no systematic study of filamentation. SRS is an insidious instability in which ion acoustic waves are generated in the plasma, and these act as a grating to reflect the incident light. This predicted effect was first found in small-scale experiments at universities and has been under intensive study at these institutions. Since SRS also generates fast electrons to preheat the core of fusion pellets, the suppression of this instability is of great benefit.

By contrast to magnetic fusion, where heat transport by electrons is anomalously fast, a major problem in laser fusion is that heat transport is anomalously slow, about an order of magnitude below the rate calculated from classical collisions. Rapid heat transport is needed laterally to smooth out irregularities in energy deposition from the laser beam, and rapid transport in the forward direction is needed to carry

heat from the critical density layer to the ablation surface, where the heat is converted to kinetic energy of ablating plasma.

That the large currents of heated electrons in a laser-irradiated target can produce multimegagauss magnetic fields has been known since the early 1960s. More recently, large magnetic fields in high-power laser experiments have been detected elegantly by Faraday rotation, and detailed probing of the field structure has been done in microwave experiments. Recent computer simulations and CO<sub>2</sub> laser experiments clearly demonstrate the spontaneous generation of magnetic fields and their effect on electron orbits and energy deposition. Since there are several different mechanisms for magnetic field production and since the problem is basically three-dimensional, progress on this complicated problem must wait for increased computational capabilities in the next decade. On the optimistic side, one can hope that the production of fields in the 100-MG range by lasers will eventually permit studies of matter in which the atomic structure has been altered by a magnetic field.

In summary, the theoretical and experimental discovery of parametric instabilities and the agreement that has been achieved between theory and experiment represent a significant advance in the development of plasma physics in the past decade. Several large problems remain to be solved, notably the general nature of heat transport in the long mean-free-path regime and the nature and effects of self-generated magnetic fields. Progress on these problems in the next decade will solidify our understanding of how intense electromagnetic waves interact with matter.

Funding for laser-plasma interaction studies in small university efforts amounts to less than \$0.6 million annually. Fortunately, these programs are supplemented by several university groups in Canada and by a sizable portion of the total effort at the three intermediate-to-large laser installations at the University of Rochester, the Naval Research Laboratory, and KMS, Inc., in Ann Arbor, Michigan. Furthermore, part of the program at the large national laboratories, Livermore and Los Alamos, has been devoted to the understanding of the basic mechanisms operative in the corona. A disproportionately small fraction (perhaps 1 percent) of the national budget on inertial confinement finds its way to programs in which the training of students takes place, and consequently the demand for personnel with experience in laser and plasma experiments is quite heavy. A doubling or tripling of support in this area is easily justified.

### Isotope Separation

The separation of isotopes by use of a plasma has been studied since the Manhattan Project of World War II. At that time the decision was made to proceed with both an electromagnetic-based system (the calutron) and a gas-dynamic-based system (the gaseous diffusion plant). Both of those techniques are still in use today for separating isotopes. The gaseous diffusion plants are large power-intensive units that are principally used for processing large quantities of material (i.e., light-water reactor fuels). A less power-intensive approach would result in a significant increment to the total U.S. power capacity. The calutrons are still in use to provide small quantities of isotopes needed for research studies or for medical purposes. The calutron is a large 180°-reflection mass spectrometer operated in a high-current regime where the space-charge forces of the ion beam are large. The calutrons provide a high degree of separation but have a limited throughput or production capability. This limited production does not allow full utilization of possible applications for isotopically pure material.

The years since the Manhattan project have been devoted to the study of basic plasma physics, and out of this have come several new approaches to electromagnetic isotope separation. These plasma-based approaches appear to overcome some of the constraints of the currently available approaches. These techniques developed within the last 10 years have been made possible by the years of basic plasma-physics research that laid the foundation. The electromagnetic separation processes are of interest since they are insensitive to specific materials, unlike laser-based processes, which depend on the electronic structure and thus are limited to specific materials.

One of these approaches is based on the ion cyclotron resonance in a uniform magnetic field. When a plasma is immersed in a magnetic field the particles undergo an oscillatory motion about the field lines. The frequency of oscillation is a characteristic depending on the charge-to-mass ratio of the ion and the strength of the magnetic field. By applying an electric field of known frequency the particle distribution functions can be modified. If the frequency is high and matches the electron cyclotron frequency, then the electrons are heated. By selectively energizing one of the species the velocity distribution can be modified to allow a physical separation to occur on a collecting structure.

A program to study this has been ongoing since 1974 at TRW and has been successful in being applied to a wide class of materials. Development of this technique for isotope separation is funded by the

Department of Energy. The primary emphasis of this program is the separation of the isotopes of uranium for nuclear-reactor fuels. These developments have been performed in a prototype facility utilizing a 2.2-tesla, 0.5-meter-long, 0.1-meter-diameter superconducting magnet system. The process utilizes an electron cyclotron resonance plasma source with the production of the metal neutrals occurring by sputtering. These heavy-ion plasma sources have operated in the range of 1-10 mA per cm<sup>2</sup>. The separation of isotopes occurs after the selective energization of one of the isotopes via ion cyclotron heating. The ion cyclotron separation process, however, occurs in a uniform magnetic field. This allows detailed comparisons of the experiments with the theoretical calculations.

The verification of isotopic selectivity by separation has been shown for several elements. For these elements macroscopic samples have been collected, removed from the device, and analyzed. Samples of potassium, nickel, indium, lead, and uranium have been collected. For the nickel separations, material has been enriched from 67.6 percent nickel-50 to 97 percent nickel-58 in a single pass. Delivery of nickel samples for use in neutron activation diagnostics has been made. In the lead separations significant enrichments were observed for the much smaller relative mass separation. In addition to the collected samples diagnostic measurements over a wide range of materials have shown the broad applicability of this technique.

Another promising approach to isotope separation has been proposed recently at Yale University. This is a vacuum-plasma-arc centrifuge. The gas-dynamic centrifuge in use for the separation of isotopes improves with rotation speed. The increases in velocity are limited by material constraints. A plasma in a magnetic field offers the possibility of a much higher rotational velocity. A major problem that occurs is the formation of a stable arc discharge along and across the magnetic field. It is the radial space-charge electric field crossed with the axial magnetic field that gives rise to the large rotation velocities. The collisional relaxation of the plasma then gives a radial profile that varies for each isotope. The basic research on the vacuum arc in an ambient magnetic field has allowed the use of the plasma centrifuge as a means for separating species.

These applications of the fundamentals of plasma physics have led to an enhanced capability. Previously isotopic uses were restricted to either very small or very large quantities. Both of these techniques offer the potential to separate intermediate quantities of material. The implications of this will evolve as the applications for isotopically selected materials emerge. Particularly in the nuclear environment of

both fission and fusion this capability can be used to reduce the structural radioactivity associated with their implementation. A second area where potential uses of isotopically engineered materials are large is in medical diagnostics. Since the advent of the CAT scanners the diagnostic information available has grown quite fast. Because of this increased diagnostic capability, and the concern over the radiation hazards of these scans, work has been proceeding rapidly with the development of alternatives. Recently dramatic advances in whole-body nuclear-magnetic-resonance (NMR) scans have been achieved. Further advances may be obtained by utilizing samples tagged with isotopes that have a given magnetic moment. Diagnostic measurements of the metabolic processes may be possible. The contributions of these outgrowths of fundamental research will be seen in the years to come.

### NONLINEAR PHENOMENA IN PLASMAS

The past 10 years have seen enormous fundamental advances in the understanding of nonlinear phenomena in plasmas. These advances have contributed greatly not only to plasma physics but also to other fields where the understanding of plasmas is important (particularly space physics and astrophysics) and have also influenced the development of nonlinear theory in general. In the following subsections we discuss some of these advances. The topics discussed are by no means meant to form a complete enumeration of these advances. Rather, our purpose is to indicate the character and flavor of the research and accomplishments in nonlinear plasma phenomena in the past decade. We therefore limit our detailed discussion to a few illustrative topics.

#### Chaos in Hamiltonian Systems

According to the Kolmogorov-Arnol'd-Moser (KAM) theorem, a small perturbation to an integrable Hamiltonian system will leave intact the topology of most of the phase-space orbits. On the other hand, it is known from numerical experiments that *sufficiently large* perturbations can convert the vast majority of the phase-space orbits to ones that have chaotic and ergodic properties on a large scale. How does the transition from one type of motion to the other occur as the perturbation is increased? This question has been of great interest to plasma physicists principally because of two applications: (1) the problem of characterizing the topology of the path followed by a magnetic field line and (2) the problem of discovering how a charged particle moves in inhomogeneous electromagnetic fields. The single most significant

advance in Hamiltonian ergodic theory in the last decade is related to the above-mentioned question. In particular, it is now fairly well understood how the last phase-space dividing orbit dies.

Beyond the destruction of the last confining phase-space orbit, plasma physicists have also been intensely interested in the diffusive properties of orbits for situations with widespread chaos. Successful techniques have recently been formulated by plasma physicists for calculating the resulting diffusion coefficients, in some cases analytically. Generally, these results show a correction to the quasi-linear estimate. Plasma-physics applications of the above basic theoretical developments have been made to the stochastic heating of plasmas by the absorption of externally launched waves, to the ergodic trajectories of wave packets of plasma waves, to the confinement of particles in the presence of collective fluctuations, to the theory of particle transport in rippled magnetic fields, and to the breakup of nested confining magnetic surfaces in fusion devices (e.g., tokamaks), among others.

### **Soliton and Related Phenomena**

In a nonlinear wave, the nonlinear effect can often balance the dispersive effect, resulting in very stable nonlinear, nondispersive pulses called solitons. These solitons emerging from collisions with each other remain unchanged except for their phases. Soliton solutions have been found in many nonlinear wave equations of physical interest using the inverse-scattering method, first discovered by plasma theorists in 1967 for solving exactly the Korteweg-deVries equation, unifying a wide range of scientific endeavor. The ion acoustic solitons and their collisions were observed experimentally in 1970. Solitons in inhomogeneous plasmas were also studied theoretically and experimentally.

Soliton research has extended to many branches of physics, such as high-energy physics, solid-state physics, and optical communications, as well as to other fields. Early studies were done with simplifying assumptions of one dimension without magnetic field, dissipation, or instabilities. Recently, solitons in two and three dimensions have been investigated. As the magnetized plasma supports many natural oscillations with rich dispersive and nonlinear properties, it is an ideal medium for soliton studies. Indeed, solitons of upper hybrid and lower hybrid waves as well as waves at cyclotron frequency and Alfvén frequency have been studied theoretically. The recently developed concepts for the studies of chaos very likely would help us to understand the behavior of more-complicated systems containing all



nonlinear, dispersive, unstable, dissipative effects. The chaotic motion of solitons would be one of the interesting future subjects.

### **Strong Langmuir Turbulence**

Weak turbulent processes, i.e., nonlinear wave-wave scattering and nonlinear Landau damping of (Langmuir) plasma waves, tend to transfer wave energy to long-wavelength modes, leading to condensation on the longest-wavelength mode. However, the long-wavelength mode is unstable to modulational instability because the ponderomotive force of the field intensity pushes on the plasma particles to create a cavity (caviton), which in turn traps more waves, leading to the collapse of Langmuir waves into patches of wave packets of the order of 10-Debye lengths. This Langmuir collapse thus provides a natural sink for the wave energy at long wavelength, and a complete description of Langmuir turbulence is within reach. Since collapse was first proposed in 1972 there have been intensive theoretical efforts because of its importance in laser-plasma and relativistic beam-plasma interaction. Evidence of cavitons was reported in microwave-plasma resonance and in beam-plasma experiments. This has since been shown to be an important mechanism also for beam-plasma interaction in space.

### **Parametric Instabilities**

Parametric decay of a large-amplitude wave into two daughter waves has been extensively studied in plasmas because of its importance to the wave heating of magnetically confined plasmas and laser-plasma coupling in inertial fusion experiments. Indeed, such parametric wave coupling is the basis of the free-electron laser described in a previous section. Many basic experiments were performed in magnetized plasmas with a wide range of pump frequencies to observe the threshold pump power and resulting anomalous absorption. In the past decade, theoretical progress has been made in the effects of plasma inhomogeneity on the threshold power for the excitation and nonlinear effects of parametric instabilities.

### **Magnetic Reconnection**

According to the "frozen-in" theorem of ideal magnetohydrodynamics (MHD), magnetic flux lines in a plasma behave as if they were tied to the motion of the bulk plasma; in this sense, magnetic topology is preserved under plasma motions. However, plasma resistivity allows a

magnetic topology change. For example, magnetic fields with opposite directions separated by a current sheet can reconnect by forming magnetic islands. Such relaxation of topological constraints, or reconnection, is often accompanied by a significant release of magnetic energy. The rate of reconnection is thus an outstanding question of plasma physics and finds application in fusion devices, solar flares, and magnetospheres. Considerable progress has been made in understanding this phenomenon in the past 10 years.

The reconnection starts with an exponential growth of a small-amplitude perturbation with growth time much shorter than resistive skin time. This exponential growth phase ceases at a relatively small island size to be followed by an algebraic rate proportional to the resistivity. Resistive MHD equations were solved numerically, and results were applied to a cylindrical or a toroidal plasma (as in a tokamak or perhaps a solar flare). The growth of the magnetic island is shown to lead to nonlinear coupling to modes of different helicities resulting in ergodic field-line behavior (as discussed in the previous section) and ensuing anomalous plasma heat loss.

In addition to the work on spontaneous reconnection, reviewed above, much notable progress has also resulted from research on *forced* reconnection, with applications to laboratory plasmas and space plasmas (e.g., knotting of magnetic field lines in turbulent solar convection zones and solar wind-magnetopause interaction).

The past decade has seen much progress on tearing modes and reconnection processes in laboratory experiments. Extensive measurements were made on the nature of tearing modes and their nonlinear consequences such as minor (internal) and major disruptions in tokamaks. Basic experiments on forced reconnection were also carried out for detailed measurements of the properties of the neutral sheet including the three-dimensional particle-distribution function and fluctuations.

#### **Turbulent Relaxation to Force-Free States**

In experiments with the reversed field pinch, it has been observed that the plasma first passes through a highly turbulent phase after which it settles down to a steady and relatively quiescent configuration with the toroidal field reversed on the outside. One of the major advances in plasma turbulence has been the understanding of the turbulent processes leading to the relaxation to the final state and of the nature of that state. This understanding has been achieved through an interplay of theoretical analysis, computer simulations, and laboratory

experiment. Within the framework of resistive MHD turbulence, the theory postulates that the quiescent, final state is the one with minimum magnetic energy subject to the constraint of magnetic helicity  $\int \mathbf{A} \cdot \mathbf{B} dV = K$  ( $\mathbf{A}$  and  $\mathbf{B}$  are the magnetic vector potential and the magnetic field, and the integration is over the entire plasma volume  $V$ ). The predicted state explains many observations in pinch experiments, and the sustainment of this state over a period much longer than the resistive skin time suggests the importance of dynamo action, a process that is being actively researched.

#### **Other Major Achievements in the Past Decade**

In addition to the above-discussed achievements of nonlinear plasma physics, we note the following equally important additional advances.

Double layers (plasma layer structures across which the electrostatic potential experiences a jump) are now fairly well understood theoretically and in laboratory experiments and have, in addition, been observed to be of great importance in space plasmas.

Collisionless shock waves (shocks in which dissipation of energy in large scales occurs by transfer to small-scale collective modes and by collisionless kinetic particle effects rather than by particle-particle collisions) are now much better understood; this knowledge has found application in space physics and astrophysics.

New approaches to the problem of determining the observed anomalously large particle and thermal transport in magnetically confined plasmas have been formulated using renormalized turbulence theory (e.g., the "direct interaction approximation").

Strange attractors have been shown to occur in certain nonlinear plasma situations.

Lie algebraic techniques have been developed to a high degree of sophistication for a variety of situations in nonlinear plasma theory.

Finally, our computational tools for examining nonlinear plasma phenomena have greatly expanded as a result of the development of innovative new numerical algorithms and concepts.

#### **PLASMA THEORY DEVELOPMENTS RELATED TO MAGNETIC CONFINEMENT**

More than half of the federal funding of plasma-physics theory over the past decade has been in connection with the magnetic-confinement approach to controlled thermonuclear fusion. Thus, many recent plasma-theory developments have been in this context. A summary of

how these developments have aided fusion research was presented earlier in this chapter. Here, we briefly review some examples of the more basic aspects of plasma theory developed in the magnetic-confinement fusion program.

### **Magnetic-Flux Geometries and Coordinate Systems**

While some magnetic-plasma-confinement schemes have an ignorable coordinate (e.g., the toroidal angle in tokamaks) the magnetic structures in most (e.g., tandem mirrors and stellarators) are fully three-dimensional. Considerable progress has been made over the past decade in developing large computer codes to calculate relevant magnetic fields with and without plasma. Further, magnetic-flux coordinates are developed from these results and, since the motion of single particles within magnetically confined plasmas is quite complex and determined by the direction of the magnetic field and its gradients, they are utilized for almost all of magnetic fusion theory. Finally, criteria have been developed for when magnetic-flux surfaces cannot be defined because the magnetic field lines become stochastic (at least in some region), typically because of the overlapping of magnetic islands that are due to resonant magnetic perturbations of incommensurate helicity or pitch.

### **Single-Particle Orbits**

In the small gyroradius expansion appropriate for most magnetically confined plasmas, the particles gyrate (in cyclotron motion), bounce (in motion along the magnetic field), and drift (in a direction perpendicular to both the magnetic field and its gradient) on successively longer time scales. Previously, these various motions have been derived by successively expanding and averaging Newton's law with a Lorentz force. Recently, a powerful (but noncanonical) Hamiltonian formulation of these orbits has been developed and utilized to calculate higher-order (in the small gyroradius expansion) corrections to the orbits. Also, the degree to which the magnetic moment is adiabatically conserved has been explored through both Hamiltonian transformations such as those indicated above and by mapping techniques. For slightly nonadiabatic motions, and also for the transition to stochastic magnetic fields, some techniques have been developed to characterize the motion in phase space in this transition to diffusive behavior in the totally stochastic quasi-linear regime.

### **Coulomb Collisional Processes**

Coulomb collisions provide the irreducible minimum transport in magnetically confined plasmas. The Coulomb collision operator is a second-order differential operator in velocity space of the Fokker-Planck type. Elaborate two-dimensional (the gyrophase angle is averaged out) computer codes have been developed over the past decade to solve for the distribution function in the presence of collisions and various velocity space loss regions. Also, the collisional scattering rates into loss cones, over potential barriers, and into pumped regions of velocity space, have been calculated analytically. When there are not substantial loss regions in velocity space, as for example in most toroidally confined plasmas, the distribution function becomes nearly Maxwellian and the spatial gradients of density and temperature provide the forces that are related through an Onsager matrix of transport coefficients to the particle and heat fluxes in the plasma. To calculate the transport coefficients in magnetized toroidal plasmas, account is taken of the gyromotion (classical transport) and bounce and drift motions (neoclassical transport) of the nearly collisionless plasmas.

### **Macroscopic Equilibria**

In plasma physics a system is said to be in macroscopic equilibrium when the forces on the plasma are in balance. Usually such force balance equilibria are calculated in an ideal magnetohydrodynamics (MHD) model. Two-dimensional magnetized plasma equilibria can often be calculated analytically, but fully three-dimensional high-pressure equilibria usually are calculated numerically or utilizing expansion parameters, usually weak toroidicity or long-thin cylinder approximations. In addition, recently some primarily numerical models have been developed for anisotropic-pressure (perpendicular pressure different from that parallel to magnetic field) MHD equilibria, such as those occurring in tandem-mirror systems.

### **Macroscopic Instabilities—Ideal Magnetohydrodynamics**

When a plasma is placed on a "magnetic hill," it often develops a collective instability of the Rayleigh-Taylor type that allows it to fall off the hill at a very rapid (hydromagnetic or sound speed) rate. Magnetically confined plasmas are usually stabilized against such rapid losses by putting them in magnetic wells of an absolute or average (over the

length of a field line) type. For the most common average magnetic wells an additional complication called a ballooning instability can arise. Here, for sufficiently high plasma pressures the plasma can collectively balloon in local magnetic-hill regions and can, at least theoretically, thereby escape the plasma-confinement region. Finally, in toroidal magnetic-confinement devices the plasma can kink into helical distortions of the original equilibria and again avoid confinement. Extensive and elaborate computer codes have been developed for investigating these possible macroinstabilities of confined plasmas.

#### **Macroscopic Instabilities—Resistive Magnetohydrodynamics**

In toroidal magnetic-confinement systems, magnetic field lines can close back on themselves after an integer number of transits around the torus, thereby forming a rational surface. The finite (i.e., nonzero) resistivity of real, slightly collisional tokamak plasmas of current interest often allows collective plasma instabilities of a kink-tearing type to form near the low-order (i.e., ratios of small integers) rational surfaces. Such collective instabilities cause magnetic islands to occur at the rational surface and to grow in width linearly with time. Since these collective modes play such a central role in the macroscopically observable behavior of tokamak discharges, a number of precise nonlinear computer codes have been developed to model them, and the code predictions have been compared in great detail with experimental observations. In general they correlate very well and are among the best examples of nonlinear plasma phenomena that are well diagnosed and understood.

#### **Microscopic (Kinetic) Instabilities and Turbulent Transport**

When the macroscopic collective plasma instabilities have been eliminated or their effects limited through careful tailoring of the magnetic-confinement system, there still remain more microscopic collective instabilities that can relax the sources of free energy (such as loss-cones and pressure gradients) in the plasma more rapidly than Coulomb collisional processes. The microscopic instabilities usually are derived from fully kinetic rather than fluid theories. In open-ended magnetic-confinement devices (e.g., magnetic mirrors) the empty loss cone in velocity space has been found to drive a wide variety of microinstabilities. These modes generally have frequencies near the ion-cyclotron frequency, so that the modes can tap the loss-cone source of free energy by destroying the constancy of the ion magnetic

moment. Correlation of numerical calculations of the quasi-linear (lowest-order nonlinear) effects of loss-cone modes with experimental results have generally confirmed the veracity of the theoretical models for these types of microinstabilities and the greatly increased loss rates they cause. In toroidal plasmas the density and temperature gradients provide the source of free energy for drift-wave-type microinstabilities in which the wave frequency is of the order of the Doppler-shifted frequency owing to the diamagnetic flows in the plasma. The expansion-free energy is tapped via additional effects that are due to finite ion gyroradii, including toroidal trapping of particles, toroidal drifts, and finite collisionality relative to the bounce motion. There has been extensive development of linear drift-wave instability theory toward making it applicable to plasmas confined in present tokamak experiments. Also, a number of nonlinear models (such as weak turbulence, strong turbulence, mode coupling, and the direct interaction approximation) of drift-wave turbulence and its effect on plasma transport have been developed. While some of these models seem to be on the right track, in that they can clarify a number of generic features of anomalous transport, there is not yet any fully satisfactory theoretical model of the anomalous radial electron heat transport process in tokamaks.

### Summary

Over the last decade, theoretical and computational tools for understanding plasma confinement and heating in magnetic systems have developed tremendously, to the level where they can now, at least in many areas (Coulomb collisional effects, equilibrium, ideal and resistive MHD global modes) closely model the experimental observations with most of the important physical phenomena included. However, turbulent phenomena within the plasma, and the transport they induce, remain the major unresolved issues.

### ATOMIC PHYSICS IN (AND FOR) PLASMAS

The importance of atomic processes in plasmas has grown with the advances in general plasma research. Several of these advances, in turn, became possible, e.g., through the development of intense neutral beams for plasma heating, i.e., via applications of atomic-physics methods. Much of the early progress in laboratory plasma physics evolved from gaseous electronics research in which a multitude of atomic and molecular reactions were investigated; likewise, major

advances in fusion research and radiation-source development have strong roots in the study of atomic collisions and spectroscopy. Atomic physicists continue to be motivated in their research by these various challenging applications and by the great need for better atomic data in astrophysical research. There is also a symbiotic relationship between basic atomic-physics research and plasma physics because high-temperature plasma devices facilitate the study of highly ionized atoms.

Examples of research areas that developed substantially in the early 1970s are analysis of atomic spectra from highly stripped metallic impurity elements, measurements of electron-ion collisional rate coefficients for ionization and recombination and corresponding calculations, detailed line radiation loss calculations for candidate materials as limiters in tokamaks, calculations of Stark broadened x-ray lines for inertial fusion density diagnostics, and investigations of schemes for laboratory x-ray lasers. Considerable progress was made in calculations of emission and absorption spectra of dense high-temperature plasmas, both for diagnostics and for energetics.

### Recent Progress

Self-consistent calculations of plasma hydrodynamics and atomic radiation have become possible and are of great value in laser fusion research and in developing intense radiation sources. Improved diagnostics of magnetic fusion plasmas were obtained by the use of newly measured magnetic dipole transitions in highly ionized iron group elements. Charge exchange from hydrogen into highly excited states of impurity ions has opened new possibilities for spatially resolved spectroscopic measurements in tokamaks. Results from plasma and crossed-beam experiments along with numerous calculations begin to provide a quantitative knowledge of dielectronic recombination. (This process tends to balance electron-ion collisional ionization of impurities in most high-temperature plasmas.) Crossed-beam measurements have become available to check the calculations of excitation cross sections for complex ions of low charge states, while plasma measurements of excitation rate coefficients were made for ions up to  $\text{Fe}^{10+}$ .

Various high-power plasma devices for the generation of intense x-ray radiation were made operational and have become test beds for the study of high-density effects on atomic radiation. Computer simulations and laboratory experiments on x-ray laser schemes have advanced to considerable complexity. Much experimental evidence for population inversion was obtained, and there were some reports of net



gain in laboratory work at high plasma densities for photon energies up to 200 eV.

### **Outstanding Research Problems**

Theoretical and experimental research leading to a self-consistent treatment of collisional and radiative interactions in dense plasmas containing highly but not completely stripped ions is required to provide sound foundations for several important applications in radiation-plasma dynamics. Effects caused by ion-ion collisions, including highly excited ions, on the overall dielectronic recombination need further study to supplement experimental work. The physics of electron collisional ionization must be more fully understood in order to develop reliable calculational tools. The importance of resonances in electron-ion scattering on rate coefficients is still to be assessed.

Cross-section measurements for excitation, ionization, and dielectronic recombination should be extended to more highly ionized atoms. Quantitative spectroscopy on well-diagnosed plasmas must be performed to test the validity of the corresponding atomic data base and reaction kinetics in real plasmas. Specifically for x-ray laser research on line pumping schemes, precision measurements of line coincidences and determinations of line shifts and widths at high-density plasma conditions are essential. Experiments designed to test reaction kinetics and to determine pump line intensities are needed as well. Corresponding investigations should be undertaken for other pumping schemes. The most promising laboratory x-ray laser scheme should then be selected and be pursued vigorously to demonstrate significant gain.

For the magnetic fusion program, sources will have to be developed to produce neutral beams of energies  $\approx 500$  keV. Also, there is a great need for magnetic-field diagnostics, which could perhaps be met, for example, by laser spectroscopy of Zeeman effects in probe-beam atoms or ions.

### **Recommendations**

Having concluded that understanding of radiation and other atomic processes in high-density, high-temperature plasmas is an interesting scientific as well as important technological goal, the main recommendations are as follows:

- Establish a center for radiation physics to provide a national focus

for research on modifications in atomic properties introduced by the presence of plasma.

- Set up a national computer data base for atomic properties. Such a truly comprehensive effort would require close cooperation among several federal agencies and ingenuity transcending that usually found in data library construction.

- Provide a dedicated facility for x-ray laser research to accelerate substantially laboratory research in this exciting area. Most likely this facility would be centered around a high-power laser, but other high-power plasma devices should be considered as well.

- Encourage the full utilization of national experimental or theoretical users facilities (Texas Tokamak—TEXT, University of Rochester Laser Facility, Magnetic Fusion Energy Computer Center) to optimize the research obtainable from limited resources.

- Improve communications and encourage collaborations between plasma and atomic physicists.

### Training

Basic atomic physics is actively pursued at many universities, typically by groups consisting of a single professor, a postdoctoral fellow, and one or two doctoral candidates, and at several national laboratories. Most often students emerge as highly specialized young scientists with little sense of the ramifications of their subjects on the broader applications, e.g., in defense or energy research. Postdoctoral research experience at one of the laboratories, centers, or national facilities would help considerably in providing the cross-fertilization required for productive research in the various applications. Closer collaboration among scientists in various disciplines is desirable, e.g., physics and astronomy departments could offer jointly atomic-physics and spectroscopy courses and could coordinate corresponding research. Course offerings should be re-examined to provide instruction in appropriate areas, e.g., in atomic structure theory, which has almost disappeared from the academic scene but may be important enough to be reintroduced into the curriculum. Closer collaboration between national laboratories and universities would heighten the awareness for such opportunities.

It is estimated that about 200 scientists in the United States are engaged in atomic physics closely related to plasma research. This is of the order of 10 percent of the entire atomic-physics community in the United States. To provide for the anticipated growth in plasma-related atomic-physics research, small increases in the fraction of new Ph.D.s

going into high-density, high-temperature plasma research would be sufficient, provided that postdoctoral training is improved.

### **Funding Levels**

The total federal funding level for atomic physics in and for plasmas, adjusted for inflation, has been approximately constant in the past 10 years and is at present estimated at \$20 million nationally. Of this amount, well over half is available in national laboratories and at most 20 percent each in universities and industrial laboratories.

### **Recommended Funding Levels**

In view of the critical importance and strong leverage of atomic physics in plasma research, a significant increase over present funding levels is recommended. Such increases should permit the establishment of the recommended new centers and facilities and a gradual increase in currently funded research and funding of promising new departures.

### **PLASMA DIAGNOSTICS**

Measurement provides the basis for physical knowledge, and the techniques for measuring the properties of plasmas, generally referred to as plasma diagnostics, have played a critical role in advancing our knowledge of plasma physics and achieving the conditions required for fusion. The problems of measuring the properties of a plasma, for example density and temperature, are great, literally astronomical. The reason is that the extreme temperatures constrain one to observe from the outside, well removed from the hot gas itself. The techniques include those of classical astronomy: that is, passively observing the radiation from the plasma, both electromagnetic, over the full range of frequencies from radio to x-ray, and particle diagnostics. In addition, one can direct beams of electromagnetic or even particle beams into the plasma and examine the response, which is the method of several powerful diagnostic techniques. Nevertheless, the task of determining with strictly noninvasive techniques the many significant plasma parameters that are varying in complex spatial and temporal patterns remains a formidable challenge.

To characterize the state of the plasma and evaluate progress toward the temperatures, densities, and energy confinement times required for fusion, many observations are required. Measurements of the temper-

atures of electrons and ions, of the densities of various ions other than hydrogen, of the currents and electric and magnetic fields within the plasma, and of the drift or rotation velocities are all needed.

Since a hot plasma at a temperature of millions of degrees is necessarily far from thermal equilibrium with its surroundings, processes to heat the plasma are essential, and transport processes, processes that seek to cool the plasma to the temperature of the surroundings, will certainly occur. Understanding these processes is vital, and they are often found to involve instabilities, fluctuations, and turbulence. This requires techniques for measuring the variations in parameters, density, temperature, and fields, over the broad range of spatial and temporal scales that characterize these several processes.

This constitutes a demand for an immense breadth and depth of diagnostic techniques. The problems and techniques are common to most magnetically confined plasmas. Diagnostics are always optimized for the parameters of each experiment, certain types of measurement are more important for some confinement geometries than others, and a few techniques are unique to particular types of devices. However, most basic measuring techniques are broadly applicable, and it suffices for this perspective to treat measurements on such devices as tokamaks, mirrors, and pinches together.

We have made remarkable progress in this task within the past two decades. At the start of this period, our techniques were truly rudimentary. Metal probes were a major diagnostic, restricted to cold, low-density, or short-lived plasmas. For hotter, higher-density plasmas, one could measure the density by interferometry but otherwise could not characterize the interior of a hot plasma in detail.

As recently as a decade ago, hot plasmas could only be grossly described. Diagnostics were restricted to providing a few numbers, such as peak or average density and temperature, and perhaps a total energy confinement time to quantify the effectiveness of magnetic containment. There was little spatial or temporal detail or basis for inferring the processes that determined the densities and temperatures observed. Great improvements have been made over the past decade in each of these respects. Techniques with greater accuracy and better resolution have been developed for each quantity and combined in a panoply of diagnostics to give a comprehensive, composite picture of a plasma. There have been few singular events to dramatize our progress, but rather a continuing series of developments and improvements that only in retrospect can be recognized for the truly momentous advances that they constitute.

### **Laser Scattering**

Foremost among diagnostic developments over the past 20 years has been the establishment of Thomson scattering as a universal standard for determining electron temperature. Made possible by the development of high-power lasers, this physically simple scattering from individual electrons in the plasma has provided straightforward and indisputable measurements of one of the most important plasma properties. Historically, it furnished the first proof that tokamaks of modest size confined hot (several million degrees) plasma, thus starting the succession of larger devices, which have now virtually reached fusion temperatures. Thomson scattering is the benchmark for temperature measurements in all devices. Over the last decade, the technique has been developed from a difficult measurement at a single point in space and time to an almost routine measurement of temperature simultaneously at many points, often giving an entire spatial profile.

### **Microwave Interferometry**

Measurements of density have also improved steadily with the development of shorter-wavelength microwave and far-infrared interferometers. These have extended the measurements to higher density and finer spatial resolution.

### **Spectroscopy**

Spectroscopy has always been an important plasma diagnostic technique, common to laboratory as well as astronomical plasmas, especially solar physics. The techniques had long been well established for cooler plasmas (much less than one million degrees), but the last decade has seen a great development in capability for spectroscopic measurements in hot plasma. Two sorts of information are generally sought spectroscopically. The first is impurity concentration—the density of ions aside from hydrogen—and the second is the inferences that can be drawn from the Doppler effect on-line shape—the temperature and velocity of the ion. Among the major developments in the past decade have been the discovery and cataloging of comparatively strong forbidden magnetic dipole lines in the spectra of highly ionized impurities. These lines are useful because they fall in the visible range of wavelengths, permitting all the established apparatuses and techniques to be applied to the high ionization states found in hot plasmas.

(The more usual allowed transitions, the counterparts of those observed in cooler plasmas, fall in the vacuum-ultraviolet to x-ray range in hot plasmas where instruments are more complex and have less resolution.) By using these forbidden lines, Doppler measurements of ion temperatures approaching 100 million degrees have been possible, as well as measurements of plasma drift and rotation. Significant developments in instrumentation have also been made, especially at ultraviolet and x-ray wavelengths. Imaging spectrometers with multiwavelength detectors combine space, time, and wavelength information. The spatial distribution of an impurity ion, an ion temperature, or a drift velocity can be obtained from a single observation.

### **Charge Exchange**

Besides measuring ion temperature by Doppler broadening, the traditional method of charge exchange has been refined and improved over the past decade. The principle is simple. Although the hydrogen in a hot plasma is nearly all ionized, a trace of neutral gas measured in parts per million remains. A neutral may exchange its electron with a hot ion, and the resulting energetic neutral, no longer confined by the magnetic field, may escape the plasma. Analysis of the energy of these neutrals indicates the temperature of the confined, hot ions. The instrumentation for these measurements has been improved greatly to detect emerging neutrals at all energies simultaneously, giving immediately the entire ion energy spectrum. This has complemented the major effort to heat plasmas by injecting energetic neutral beams. The charge-exchange diagnostics have documented our thorough understanding of beam penetration and transfer of energy from the beam to the plasma. In reciprocal fashion, injected neutral beams have proven to be a valuable diagnostic in their own right, a capability that is only now being developed fully. Attenuation of the beam as it passes through the plasma gives valuable information, the augmentation of the charge-exchange signal by the injected neutrals gives ion temperatures with superior spatial resolution, and the neutrals drive charge-exchange reactions with impurity ions in the plasma, which have opened new possibilities for spectroscopic diagnostics with unique spatial resolution.

### **Neutrons and Alpha Particles**

Another major diagnostic development of the last decade has been occasioned by the fusion reaction itself. As temperatures have ap-

proached those required for fusion power, deuterium discharges have begun to produce detectable fusion. The energy spectrum of the emerging alpha particles in mirror machines has been most informative, and the production of neutrons is used generally to infer ion temperatures. Developing capability to measure the energy spectra of the neutrons is providing more-certain measurements.

### **Blackbody and Plasma-Well Interactions**

Reflecting the steady increase in sophistication of diagnostics have been developments like the demonstration that many plasmas behave as blackbodies at the electron cyclotron frequency, making a simple measurement of electron temperature possible. Techniques from surface physics have been adapted to study the interaction of plasma with the walls of the vacuum vessel and the introduction of impurities into the plasma. Broadband measurements of the total radiation from the plasma have been combined with various other diagnostics to allow detailed analyses of energy flows within a plasma. In the best cases, diagnostics are now sufficiently complete to imply values for transport rates, the thermal conductivities of ions and electrons in a particular experiment.

### **Heavy-Ion Diagnostics**

One of the most obvious characteristic parameters of an electrically conducting medium like a plasma is the electric potential or electric field within the medium, but this has been notoriously difficult to determine for hot plasmas. One technique, the use of an energetic heavy ion beam, has been developed within the past 5 years and demonstrated on mirror machines and some other devices. Much more is expected from this diagnostic in the next decade.

### **Time-Resolved Plasma Activity**

All of these diagnostics describe the equilibrium state of the plasma, including such parameters as the densities and temperatures of the components, with spatial resolution but on a time scale that is characteristic of the equilibrium. They do not reveal variations on a rapid time or spatial scale, yet we know such variations are phenomena of major importance in plasmas. Experimentally, fluctuations of some sort are seen in nearly every type of plasma. Theoretically, every plasma configuration seems subject to some sort of linear instability,

which may limit or destroy the plasma or evolve into some nonlinear turbulent state. These are presumably among the processes that determine the effectiveness of energy confinement in a particular configuration. Such fluctuations and instabilities have been detected in many ways. In the easiest cases, they can be seen as oscillations in the magnetic field outside the plasma or they are coupled to an electromagnetic wave, which can propagate through the plasma and be detected outside. A serendipitous indication of internal plasma oscillations was provided by simple x-ray detectors on tokamaks in 1974. The detectors are sensitive principally to temperature variations, and their application to tokamaks, coupled with analysis methods akin to those for the tomographs that have revolutionized medical x-ray diagnosis, have produced images of highly complex modes within the plasma that evolve on times of milliseconds.

#### **Scattering from Collective Fluctuations**

A systematic and versatile method of observing density variations within the plasma is to scatter an electromagnetic wave from the fluctuations. Using a laser source, sufficient scattered signal can be obtained. In principle, the frequency, wavelength, and intensity of fluctuations in a chosen region of plasma can all be obtained by this method. Unfortunately, the several constraints for the application of the method have required the use of submillimeter microwaves (far infrared) for many plasmas of interest. Exploitation has waited the development of suitable laser sources and detector technology within the last few years. Its potential is just beginning to be realized.

#### **Data Acquisition and Instrumentation**

A crucial technological development that underlies all of these diagnostics has been the commercial development of advanced computerized data-acquisition and -processing systems over the last decade. Although one could imagine implementing any one of these diagnostics, albeit with difficulty, without computers, computerized systems are essential for combining diagnostics to give a complete characterization of the plasma in any major device. The volume of data and the sophistication of analysis required to obtain intelligible results from the raw data both require computers. The consequences for experimental operation and physical understanding have been immense. Immediate processing provides a characterization of the plasma that makes possible far more intelligent and productive opera-



tion of the whole experiment. It also permits each diagnostic to be optimized quickly, and makes even subtle malfunctions quickly apparent. Compared with experiments a decade ago, more data, by several orders of magnitude, are collected per day of experimental operation. Furthermore, a larger fraction is analyzed to yield useful results. Although this section concerns the developments in plasma diagnostics for magnetic fusion, we should mention that a comparable fraction of the inertial fusion effort is also devoted to diagnostics. In inertial fusion, x-ray microscopy and x-ray and particle spectrometers are the principal techniques, and these have been developed to a high degree of sophistication.

Advances in picosecond streak cameras have been inspired by the need for extreme time resolution. Perhaps the most impressive accomplishment, however, was the use of microscopic zone plates to focus the alpha-particle products of a laser-induced implosion, showing that true DT fusion indeed took place.

### Desiderata

As impressive as our gains in diagnostic capability and consequent understanding have been, they often serve to underscore those areas where improvement is needed. Several important plasma parameters still elude measurement, and novel, innovative methods for their measurement remain to be devised. At the top of this list are local current density and magnetic field within a plasma, for which measurements of both average and fluctuating quantities are sorely needed. A technique to measure the electron velocity distribution function would be extremely useful, as would a more generally applicable method for measuring plasma potential and electric field, the heavy-ion-beam probe being impractical for many plasmas.

In addition to completely new diagnostics, new methods or extensions of present methods to give improved spatial and temporal resolution are needed for all plasma parameters. The ideal diagnostic would measure a given parameter, e.g., electron temperature, at each point and time throughout an experiment. Instead, we are able to determine only a limited set of such data. The striving to this ideal is not purely academic; every time we have made an improvement in measuring capability, we have discovered new phenomena and deepened our understanding. Areas that are almost certain to be fruitful in this regard include better measurements of the fluctuations of turbulence in plasmas and more accurate, fine-grain measurements of the spatial variations of density and temperature, for it is the gradients in

the quantities that presumably determine the efficiency of energy confinement.

To advance our knowledge of plasmas and make effective use of major fusion experiments to establish a firm scientific basis for fusion power, we recommend three policies:

- Greater effort be devoted to the development of specific novel and improved diagnostic methods. Most often diagnostics are developed for a specific experiment and only to the minimal extent required. Novel diagnostics can be difficult to support if they lack immediate application to a specific experiment. One example, but by no means the only one, of techniques with great and diverse diagnostic promise are those stemming from the development of improved far-infrared technology.

- Higher priority be given diagnostics during the planning and construction of experimental facilities. Historically, diagnostics have not always been planned with a device or have been deferred during construction to make costs appear to be within budget. As a result, machines often begin with limited capability and are delayed in reaching their full potential. The essential role of diagnostics and their development must be fully appreciated.

- Additional effort be devoted to computerized data systems to cope with the rapidly expanding capabilities required. CAMAC has been accepted as a *de facto* standard in all major laboratories, but much more development and standardization for both hardware and software is required to provide the capabilities required for the future without duplication and great waste of resources. Extant and foreseeable diagnostics will make it possible to produce greatly increased amounts of useful data from experiments in the coming decade. More systematic approaches will be required to manage this information.

The actual expenditures for diagnostics over the past decade cannot be realistically isolated. The only budget specifically allocated to diagnostic development is a small program within the Division of Applied Plasma Physics in the Office of Fusion Energy (DOE). This is currently funded at a level of \$5 million per year and has totaled little more than \$30 million over the past 10 years. It represents only a small fraction of the effort devoted to diagnostics. Most diagnostics are funded quite properly as part of the construction and operation of the experiment to which they are attached; no separate budget figures can be extracted. The development, fabrication, operation, and incremental improvements in a typical diagnostic are inextricably associated with the total experimental operation. This has been a very desirable

*modus operandi*, for it ensures that diagnostics are practical, usable, and utilized on experiments. It should be complemented and supplemented by an increased effort, independent of specific devices, devoted to diagnostics that require longer development before being ready for application to experiments and to diagnostic and computer developments, which should be generally applicable or standardized.

### STRONGLY COUPLED PLASMA PHYSICS

A strongly coupled plasma is a form of dense ionized matter in which coulombic correlations among the charged particles determine bulk and dynamic properties. The interaction coupling parameter defined as the ratio of the average coulomb potential energy between particles to the average kinetic energy for such a plasma is greater than unity and for some systems much greater than unity. This degree of coupling is in marked contrast to the more commonly studied laboratory plasmas, which are low density and weakly coupled. A strongly coupled plasma thus is a fluid that resembles a neutral electrically conducting liquid. At sufficiently high density the coulombic correlations become so strong that the fluid undergoes a first-order phase transition to a lattice.

Much of the matter in the universe is in the strongly coupled plasma state since stellar interiors are highly ionized and often at very high density. Physical systems that may be described as strongly coupled plasmas include the following:

- (i) Inertial-confinement fusion targets compressed by lasers;
- (ii) Interiors of large planets;
- (iii) Stars in late stages of evolution, e.g., red giants;
- (iv) Liquid metals;
- (v) White dwarf interiors; and
- (vi) Neutron star crusts.

### History

It was recognized some decades ago that matter at extreme densities has a significant limiting form in which the electrons because of the large Fermi energy become nearly uniform in density. In this limit, one will have a system of heavy (hence classical) ions or nuclei moving in a background of electrons that provide electrical neutrality and stability due to the large electronic pressure. For ionic matter formed from a single element and a neutralizing background of electrons this limit is called the one-component classical plasma (OCP). It has been the

subject of intense analytic and numerical study since it is the prototype strongly coupled plasma and is essential for understanding the properties of the physical systems mentioned above. In the universe the OCP limit is approached only in white dwarf star interiors, and thus it is difficult to reach for experiments on the Earth. Conceptually the OCP limit, however, plays the same role for strongly coupled plasmas that the hard-sphere fluid plays for the theory of neutral liquids.

Cluster expansion methods used for dense gases and liquid-state theory proved in the 1960s to be not particularly useful for strongly coupled plasmas, and numerical simulation methods were developed. In 1966, the availability of large computers at the Lawrence Livermore Laboratory made it possible to carry out the first detailed study of the OCP fluid state and to give some hint of the phase transition. The Monte Carlo method was used. In this procedure a few hundred charged particles are moved randomly in a three-dimensional cell in a manner to give average thermodynamic properties equivalent to the canonical ensemble of statistical mechanics. The simulation process gives numerical results for the coulombic interaction energy and the pair distribution function. The data thus obtained should be regarded as the results of numerical experiments, which are subject to problems typical of real experiments. Although the numerical simulation methods are slow and expensive, the data obtained have been invaluable and have spurred major theoretical understanding of the properties of the OCP and related strongly coupled coulombic systems.

The OCP equation of state was applied to white dwarf star structure calculations and gave rise to the suggestion that the center of these stars might be crystallized. The OCP pair distribution data were Fourier analyzed to give the OCP plasma structure factor, which was then used in realistic calculations of various transport properties such as diffusion, electrical conductivity, thermal conductivity, and viscosity. Applications of the OCP results were made to red giant stars and to calculations of dense plasmas that it was hoped would be produced in inertial-confinement fusion targets. In 1973, the OCP data from the Monte Carlo study were used to improve significantly the theory of thermonuclear reaction rates in stars. In the early 1970s the Monte Carlo method was extended away from the OCP limit to allow the neutralizing electrons to be treated as a polarizable fluid that partially screens each ion. This simulation gave rise to a much better understanding of the evolution and structure of Jupiter.

The availability of good numerical experiments for the OCP fluid spurred efforts to use the integral equations of liquid-state theory to the OCP and related strongly coupled plasmas. The hyper-netted chain

(HNC) equation was solved to great accuracy in 1974, and the results were found to be remarkably close to the Monte Carlo results. The integral equation approach is advantageous because it is about a thousand times faster than the more exact simulation methods. In fact for numerous applications it was found that the HNC results were adequate for practical calculations of the equation of state of ionic mixtures and for electrical conductivity.

In the late 1970s, it was found experimentally that electrons could be trapped on the surface of liquid helium and thus confined to motion on a two-dimensional surface. It was found that the electron density could be increased so that the resulting two-dimensional plasma could be produced in weak coupling and then as a strongly coupled plasma, which finally exhibited a two-dimensional phase transition. This system was particularly interesting since it provided a clean method of studying strong coulombic correlations, albeit in two dimensions. Two-dimensional Monte Carlo simulations were carried out for both the fluid and solid phases, and the density for the phase transition was found to be in good agreement with the experimental observation. As in the three-dimensional case, the HNC equation was applied to the two-dimensional electrons and was found to be in good agreement with the more expensive numerical simulations.

### Recent Progress

At the Livermore and Los Alamos Laboratories the Monte Carlo simulation technique has been very much refined. The availability of the Cray computers, currently the world's largest, made it possible to study the OCP fluid and solid phases with simulations involving up to a thousand particles and tens of millions of configurations to be averaged. This is a model involving heavy (classical) ions moving in a nearly uniform density background of electrons. The internal energy results are good to four- and five-figure accuracy, and the pair distribution function is known everywhere to better than a fraction of 1 percent. The OCP thermodynamic functions are now known better than those for any other simple liquid, including even the well-studied hard-sphere system.

With the very exact Monte Carlo results as a guide the HNC equation was modified by the inclusion of an approximate bridge graph function. This is an integral equation approach to the problem that computes more rapidly (by a factor of  $10^3$ ). When solved numerically, the internal energy from this equation agrees with the Monte Carlo results to within the level of the Monte Carlo noise. This is a

remarkable agreement of a theoretical liquid-state calculation with numerical experiment, which opens the way for a wide variety of quantitative calculations of thermodynamic properties and transport properties of dense partially ionized plasmas and liquid metals.

Spectral lines emitted by highly compressed targets in laser fusion experiments have provided another significant and useful connection between theory and experiment. At the densities and temperatures reached in these compression experiments, elements such as argon are ionized to the point that only one or two electrons are still bound. Thus it is now possible to study spectral lines from hydrogenic and helium-like argon. These lines are in the x-ray region and are broadened by the Stark effect owing to neighboring ions in the plasma. A by-product of the Monte Carlo simulation of the OCP has been an easy calculation of the electric microfield distribution needed for the calculation of spectral line shapes. The experimental measurement of several lines of the Lyman series has given a reasonable test of current line-broadening theories and the usefulness of the Monte Carlo microfield for predicting spectral line shapes from highly ionized strongly coupled plasmas.

#### Outlook for the Next 10 Years

Future improvement on present-day understanding of ionic matter will probably come about by a fully quantum treatment of strongly coupled plasmas. Considerable progress has already been made on the quantum many-body problem at zero temperature, and the properties of the electron gas at  $T = 0$  have been computed. Work is proceeding rapidly on electron and proton systems, e.g., hydrogen, and it is expected that a detailed understanding of the formation of metallic hydrogen at high pressure will result. The next stage of this kind of investigation will require practical computing procedures for the quantum treatment of electrons and point nuclei at finite temperature, as for example, using the Feynman path integral method. As with the classical numerical simulation methods, the quantum plasma simulations will be costly and time-consuming numerical experiments.

Clearly, strongly coupled plasma physics is an important area of research because of its astrophysical applications and technological applications. The level of research in this area is increasing rapidly in several countries around the world, and U.S. leadership is by no means assured during the 1980s. In the United States much of the important work in this field is done at national laboratories because of the availability of large computers and large laser systems. Only a few American universities have good research efforts where students can

gain experience with established researchers. In spite of the U.S. advantage in large computers, a French group continues to make fundamental advances in both computation and basic theory. Several groups in Japan are attacking problems in strongly coupled plasmas such as simulations on liquid metals, laser-produced plasmas, and transport calculations for astrophysical plasmas. With the advent of the new Japanese supercomputers, it is certain that researchers in possession of such computers, for example the Japanese groups, will become leaders in numerical simulation with both classical and quantum methods. For the United States to continue to make significant contributions to strongly coupled plasma phenomena, it would be advisable to strengthen support for this area of physics in U.S. universities.

### NONNEUTRAL PLASMAS

A nonneutral plasma is a collection of charges that satisfy the usual many-body criterion to be a plasma but in which there is *not* overall charge neutrality. These systems usually have intense self-electric fields and may also have intense self-magnetic fields. They are called plasmas, even though they are not charge neutral, because they exhibit many of the collective phenomena characteristic of a neutral plasma. For example, many types of waves that are supported by a neutral plasma have nearly identical counterparts in nonneutral plasmas. For example, nonneutral plasmas exhibit the phenomena of Debye shielding, that is, the plasma particles act collectively to cancel (or shield) the field of an extra charge placed in the plasma.

Nonneutral plasmas in the form of electron beams have been used in applications such as microwave-generating devices for many years (see section on Coherent Free-Electron Radiation Sources), but it was only within the last decade that nonneutral plasma physics was recognized as a separate subfield. Theoretical foundations of the subject were provided by many papers written in the 1960s. At the beginning of the 1970s, interest was stimulated by several experimental programs—on toroidal confinement at the AVCO Corporation and on mirror confinement at the University of Maryland. In both cases confinement times of about 10 ms were reported.

During the 1970s, theoretical studies continued on equilibria and stability for confinement in various magnetic field configurations and for relativistic as well as nonrelativistic plasma, the analysis of waves, and the development of transport theories. The experimental studies at AVCO and the University of Maryland terminated. Further studies of

magnetic confinement were carried out at Maxwell Laboratories, Inc., and the University of California, Irvine (UCI). A new experiment on a hybrid confinement system (Penning trap) was started at University of California, San Diego (UCSD). In the pure magnetic confinement experiments magnetic compression always produced a plasma of high density ( $n \sim 10^{10}$ - $10^{11}$  cm $^{-3}$ ) and high temperature ( $10^4$ - $10^6$  eV). In the hybrid trap with confinement by electrostatic fields in one direction and magnetic fields in the other directions, densities are typically of order  $10^7$ - $10^8$  cm $^{-3}$  and the temperature is less than 1 eV. The pure electron plasma experiments are very clean and yield experimental data of high precision compared with conventional plasma experiments where ions because of their large mass create substantial difficulties for experiments and theory. Similar remarks apply to experiments with a small density of ions compared with the electron density. At present, experimental programs on the physics of nonneutral plasmas exist at UCSD, UCI, University of California, Los Angeles, and the University of North Carolina.

Although nonneutral plasmas have many properties in common with neutral plasmas, there are some interesting differences. For example, a nonneutral plasma consisting of only electrons (or only ions) can be confined forever, at least in principle, and this is definitely not the case for a neutral plasma. In confinement geometries for which the confining electric and magnetic fields have cylindrical symmetry, general stability and confinement theorems prove that a pure electron plasma (or a pure ion plasma) simply cannot escape. Of course, actual confinement systems cannot have perfect cylindrical symmetry; small construction and field errors or end effects break the cylindrical symmetry and produce a slow loss of the plasma. Nevertheless, pure electron plasmas have been confined for periods as long as a day, which is many orders of magnitude longer than the few second confinement times characteristic of neutral plasmas. (See Chapter 4.)

Another difference concerns the possibility of cooling a pure electron plasma to very low temperatures, that is, to a degree or so above absolute zero. For a pure electron plasma, the electrons cannot recombine with ions to form atoms (as electrons would in a neutral plasma) since there are no ions in the confinement regions. Theory predicts that as the temperature of a pure electron plasma is reduced, the electrons will enter the liquid state and then the crystal state, that is, one will obtain a pure electron liquid and a pure electron crystal. An experimental program is under way at UCSD to realize these new states of matter in the laboratory, and there is preliminary evidence that the liquid state may have been obtained. Similar experiments are



being carried out with a pure ion plasma at the National Bureau of Standards Laboratory in Boulder, Colorado. This general area of research should be quite exciting in the next few years. Note that this area of research overlaps and complements studies discussed in the section on Strongly Coupled Plasma Physics.

Many applications of nonneutral plasmas have developed in the 1970s—to a large extent the applications are much older and the importance of the nonneutral plasma was recognized more recently.

For example, it was recognized that in a simple mirror the confinement in the axial direction is electrostatic; this led to the invention of the tandem mirror and the further refinement of thermal barriers to reduce thermal conduction along the field lines.

In the large pulse power machines, the importance of magnetic insulation was recognized. In a magnetically insulated transmission line, the electric fields are so large that copious field emission of electrons takes place; however, with suitable magnetic fields the electrons are confined and do not short out the line. Magnetic insulation (confinement) plays a central role in power flow and ultimately limits the concentration of power. It also plays a key role in the design of ion diodes because the electron flow must be inhibited. The operation of relativistic magnetrons also depends critically on the principles of magnetic insulation.

In the development of high-current accelerators, the toroidal confinement of a pure electron plasma is of central importance and is being studied at NRL and UCI in programs to develop a modified Betatron.

The electrostatic field of a confined column of electrons can be used to focus strongly a beam of ions. This is called a Gabor lens and was invented in 1947. Recent experiments at the University of Oregon have focused an millielectron-volt beam of ions to about 10 m with such a lens. This principle is central in efforts to develop compact ion accelerators called collective focusing accelerators; a linear accelerator is being studied at SNL (PULSELAC) and a cyclic acceleration experiment is under way at UCI (CFIA). (See section on Collective Focusing Accelerators.)

A radial electric field together with an axial magnetic field can produce rotation of a plasma column that is much more rapid than a mechanical centrifuge can achieve. The radial electric field is associated with a nonneutral plasma. The plasma-arc centrifuge for isotopic separation is being studied at Yale University.

In summary, the last decade saw the field of nonneutral plasma physics established and a substantial base of knowledge developed. Techniques were borrowed from neutral plasma physics, and rapid

progress was made in understanding many of the similarities between nonneutral and neutral plasmas. Also, important differences were identified, and it was realized that some of these offer unique opportunity for interesting physics research and for useful application. The occurrence of nonneutral plasma was recognized in many important applications. We expect that plasma physics will be broadened and enriched by the study and application in the next decade of nonneutral plasmas.

# 4

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## Fusion Plasma Confinement and Heating

### SCOPE AND OBJECTIVES OF FUSION PLASMA RESEARCH

#### Introduction

Thermonuclear fusion is one of the very few options available that can provide for mankind's energy needs in the very long term. Based on essentially inexhaustible (billion-year) fuel reserves of near-zero cost, fusion power is perceived to offer many advantages over alternatives, such as solar power or the breeder reactor. Environmentally, fusion has the potential to provide a much safer system than the breeder reactor, with respect both to the safety of the plant itself and to all aspects of its fuel cycle: fissionable materials are not involved; fusion's "ashes" are inert; and radioactivity associated with plant operation can be minimized and made to be short lived.

Recognition of the major advantages of fusion is reflected in the fact that fusion has become a major international research effort. There are large fusion programs in Western Europe, in the Soviet Union, and in Japan (where fusion has been declared to be a national goal). The U.S. fusion program is recognized worldwide as being preeminent, largely as a result of a foresighted expansion of the program about a decade ago. If the present momentum can be maintained, the United States could also become the world leader in the construction and deployment of fusion power systems.

Although the study of naturally occurring high-temperature plasmas is of considerable scientific interest of itself, it has been the quest for controlled fusion power that has been the dominant influence on research in plasma confinement and heating for three decades. Fusion plasmas require very high temperatures, higher even than the center of the Sun, and must be confined either by very strong magnetic fields or by compression to ultra-high particle densities.

The basic theoretical properties of a magnetized plasma, and the conditions under which thermonuclear power can be released, were fairly well understood at the outset of fusion research in the early 1950s. In retrospect, however, it is clear that the experimental difficulties, as well as the vicissitudes of plasma behavior, were greatly underestimated. By the late-1950s, it became clear that more basic research would be required before any practical, large-scale fusion device would be possible. Theoretical efforts directed toward the fundamental understanding of plasma confinement and heating received high priority, and these efforts were reinforced by many experiments directed more toward the development of plasma physics than toward the immediate objective of fusion power. By the late-1960s, the theoretical understanding of magnetically confined plasmas had advanced impressively, but there was still no firm experimental basis for the extrapolation of any magnetic-confinement scheme to the plasma conditions regarded as being necessary for a practical fusion reactor.

The prospects for success in fusion research turned dramatically better toward the end of the 1960s and have improved steadily throughout the 1970s and early 1980s as a result of the experimental demonstration of high-temperature, well-confined plasmas in a number of devices in several different countries. Plasma parameters in some of today's fusion devices are within reach of those required in an actual reactor. However, while empirical scalings deduced from these experiments may perhaps prove adequate to bridge the remaining gap to the reactor regime, the improvement in predictive capabilities that would result from a more thorough theoretical understanding of the behavior of confined plasmas—an understanding that has tended to lag behind the experimental achievements—would greatly enhance confidence in detailed reactor projections and would aid in the design of the most advantageous fusion systems.

Progress in the much younger discipline of inertial confinement—which had its origins in the weapons programs of the 1950s but became a serious candidate for power production and other civilian applications only in the late 1960s—has been sustained by the remarkable advances that have occurred in recent years in the development of

very-high-power lasers and intense beams of energetic particles. In inertial confinement, these lasers or particle beams are used to compress a tiny pellet of fusion fuel to ultra-high density; magnetic fields are not involved. Progress in the science of inertial confinement has been greatly facilitated by the development of highly sophisticated diagnostic methods, which can make measurements of physical quantities in microscopic regions of space in times as short as a trillionth of a second. Whether useful net energy gain can be achieved by inertial confinement remains uncertain, but the techniques have other important civilian applications, such as the production of fissile fuel.

The experimental science of plasma confinement now rests on a solid theoretical understanding of the macroscopic dynamics of nonuniform plasmas. Indeed, to an ever-increasing extent, important experimental advances in plasma confinement are the result of some new insight into the theoretical properties of some particular confinement configuration. This close link between the physical processes of importance and the geometry of the confinement configuration is intrinsic to fusion research and implies that any discussion of progress in fusion must be organized by confinement concept; such is the approach adopted in this chapter.

Progress in the experimental science of plasma heating has been the result both of technological advances and of greatly improved understanding of the microscopic processes underlying the propagation and deposition of energy in nonuniform plasmas; plasma-heating techniques are relatively insensitive to geometrical configuration and can often be applied to a number of different confinement concepts.

Plasma confinement and heating are not the only issues to be resolved before a practical fusion reactor can be built. However, for the first time in the history of fusion research, there seems now to be a substantial and reliable experimental basis for the detailed description of the fundamental scientific requirements of such a reactor—at least in the case of the magnetic-confinement approaches.

### The Fusion Process

The reaction most likely to be used in a first-generation fusion reactor brings together the charged nuclei of deuterium (D) and tritium (T), which react to form an energetic charged nucleus of helium ( $^4\text{He}$ , sometimes called an alpha particle) and an ultra-energetic neutron (n), according to the relationship



Creation of fusion reactor fuel—a plasma of positively charged deute-

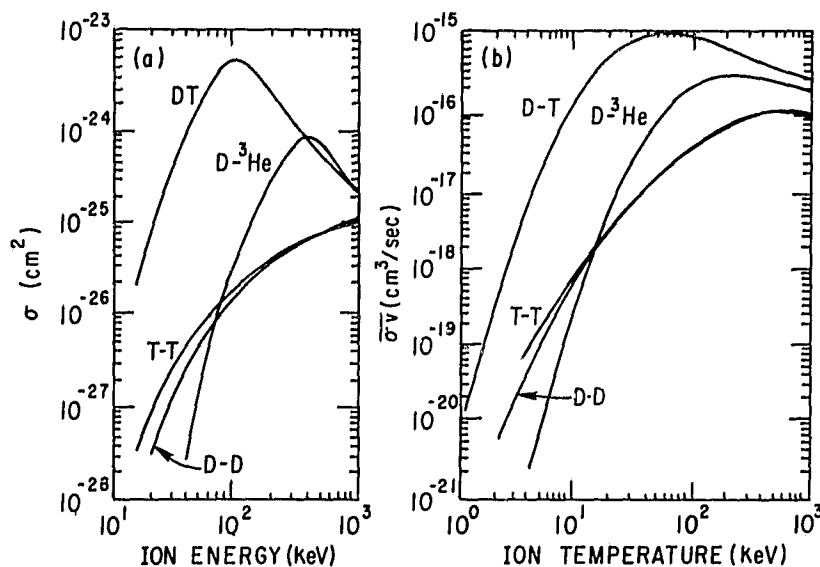


FIGURE 4.1 (a) The cross section  $\sigma$  for various fusion reactions as a function of the relative energy of the colliding ions. (b) The quantity  $\sigma v$  that is a measure of the fusion reaction rate averaged over thermal distributions of colliding ions, as a function of ion temperature.

rium and tritium nuclei and neutralizing electrons—is facilitated by the dissociation of atoms into their electrically charged constituents at temperatures above 1 electron volt [eV (1 electron volt equals about  $10^4$  degrees Celsius)]. However, before the positively charged deuterium and tritium nuclei can fuse, the electrostatic forces of repulsion between them must be overcome. Figure 4.1(a) shows that, for the cross section of the D-T reaction to be at its maximum, the relative kinetic energy of the colliding nuclei (ions) must be about 100 kiloelectron volts [keV ( $10^9$  degrees Celsius)]. In a thermal distribution of ion energies, fusion reactions occur predominantly among the most energetic (suprathermal) particles; Figure 4.1(b) shows that the reaction rate reaches a broad maximum for ion temperatures in the range 20 to 100 keV. In terms of the potential overall energetics of the fusion process, an energy investment even of 100 keV in each reacting nucleus is quite modest, since the fusion energy released by each reaction is almost 200 times greater, namely 17.6 million eV [MeV ( $10^{12}$  degrees Celsius)]. In terms of the actual realization of fusion conditions, however, the requirements are formidable, since the plasma must not only be heated to a temperature in excess of 10 keV (about  $10^8$

degrees Celsius), but the energy must also be confined (that is, contained within the plasma, without being carried to the walls of the containing vessel) for times long enough for the relatively infrequent fusion reactions to occur.

Eventually, it seems possible that the deuterium-tritium reaction might be replaced by fusion processes that are more difficult to achieve but have even more desirable environmental features. For example, use of the deuterium-deuterium reaction would eliminate the need for regeneration of tritium fuel in the fusion reactor—by means of a process using lithium compounds that is well understood, in principle, but that complicates the design of the heat-producing fusion-reactor “blanket.” Another reaction—that between deuterium and helium-3—is an example of a fusion reaction that releases its energy entirely in the form of charged particles, rather than neutrons, thereby offering the possibility, at least in principle, of direct conversion of the fusion energy into electrical energy. However, Figure 4.1 shows that the cross sections and reaction rates for these reactions are as much as a factor of 10 lower than those for the deuterium-tritium reaction.

An important figure of merit for an experimental fusion reactor is the ratio of the output power derived from the fusion reactions to the input required to heat the plasma. This ratio, called the energy multiplication factor  $Q$ , depends on the fraction of the hot nuclei that are able to fuse during the time it would take for the plasma to lose its energy. Since fusion reactions are two-particle reactions, the  $Q$ -value is found to depend on a confinement parameter (sometimes called the Lawson parameter), the product of the plasma (electron) density and the energy confinement time; the  $Q$ -value depends, of course, also on the ion temperature. Figure 4.2 shows the requirements for thermalized breakeven (a  $Q$ -value of unity for a thermal distribution of reacting particle energies) in a deuterium-tritium plasma, as a function of the spatially averaged ion temperature and the confinement parameter. For example, thermalized breakeven in a plasma with an average ion temperature of 10 keV requires that the confinement parameter exceed  $6 \times 10^{13}$  particles per cubic centimeter seconds.

Approaches to fusion that utilize magnetic confinement divide into two main classes: (i) those whose goal is a plasma with a density of somewhat more than  $10^{14}$  particles per cubic centimeter and a confinement time of about a second (tokamaks, stellarators, mirrors, and bumpy tori) and (ii) those that have the potential for much higher-density plasma, typically  $10^{15}$  particles per cubic centimeter or more, with correspondingly reduced requirements on confinement time, typically a tenth of a second or less (reversed-field pinches, compact toroids).

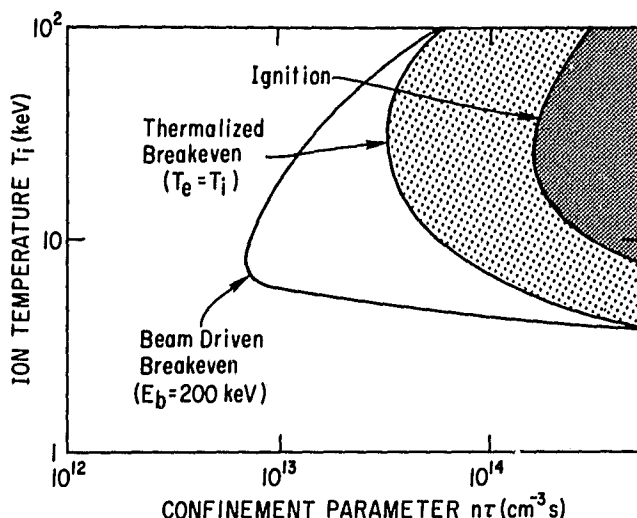


FIGURE 4.2 The ion temperature  $T_i$  and confinement parameter  $n\tau$  required for D-T ignition, for breakeven in a thermal plasma, and for breakeven in a beam-driven plasma (beam energy 200 keV). Here,  $n$  is the electron density and  $\tau$  the energy confinement time.

Approaches to fusion that utilize inertial confinement seek to compress a deuterium-tritium pellet to a density of about  $10^{25}$  particles per cubic centimeter and to maintain a thermonuclear "burn" at fusion temperatures for about  $10^{-9}$  s before the pellet disassembles.

In the case of the lower-density magnetic approaches, where the plasma can be penetrated by beams of energetic particles, a significant improvement in the confinement requirement—by almost a factor of 10—can be realized by using reacting beams of very high energy to heat the plasma. Figure 4.2 also shows the requirements for this kind of beam-driven breakeven, for the case where a tritium plasma is heated by a 200-keV deuterium beam.

On the other hand, the  $Q$ -value of a plasma increases rapidly after the confinement parameter exceeds the break-even threshold, because 20 percent of the energy produced in fusion reactions between deuterium and tritium is released in the form of energetic helium nuclei (alpha particles), which can be retained in the plasma, thereby amplifying the input power available for heating. Eventually, the fusion reactions become able to maintain the temperature of the plasma without any input of heating power, and the  $Q$ -value becomes infinite; at that point, the plasma is said to be ignited. Figure 4.2 shows that



ignition of a deuterium-tritium plasma with an average ion temperature of 10 keV requires that the confinement parameter reach  $3 \times 10^{14}$  particles per cubic centimeter seconds. At temperatures below 5 keV the fusion reactions are unable to sustain the plasma temperature against losses of energy by radiation, with a result that ignition becomes impossible even if the energy carried from the plasma by conduction and convection is negligible.

From a practical viewpoint, taking into account the efficiency for conversion of fusion energy into electrical energy and the efficiency of plasma heating, a fusion reactor can produce useful net power if the  $Q$ -value lies in the range 10-20. (In inertial confinement fusion, a pellet-plasma  $Q$ -value of a hundred or more is needed to compensate for driver and implosion inefficiencies.)

The principal approaches to fusion—magnetic confinement utilizing either toroidal or mirror magnetic fields and inertial confinement—are illustrated in Figure 4.3.

### Magnetic Confinement

The most successful approach to the confinement of plasma at fusion temperatures makes use of the fact that charged particles tend to gyrate in tight spirals along the lines of force in a magnetic field. The radius of gyration of a deuterium ion with an energy of 10 keV in a magnetic field of strength 20 kilogauss (kG) is only 1 centimeter (cm), implying that the particles of a fusion plasma can be readily confined in a suitably shaped "magnetic bottle" of modest size and modest field strength. However, a plasma at fusion densities and fusion temperatures has a kinetic pressure (density times temperature) that is large enough to depress the magnetic pressure of the confining magnetic field by a significant factor, called beta, as illustrated in Figure 4.4. The plasma beta-value that is attainable depends mainly on the shape of the magnetic bottle.

For a magnetic field strength of 50 kG—typical of that proposed in many reactor designs—the realization of a beta-value of 6 percent would provide a plasma with a pressure of about 6 atmospheres. This would correspond, for example, to an average plasma density of  $2 \times 10^{14}$  particles per cubic centimeter and an average ion and electron temperature of 10 keV, requiring an energy confinement time of about 1.5 s for ignition. The fusion power density in a deuterium-tritium plasma would be about 5 megawatts per cubic meter (MW/m<sup>3</sup>)—a practical value from an engineering viewpoint. Fusion-reactor concepts involving substantially higher beta-values offer greatly improved

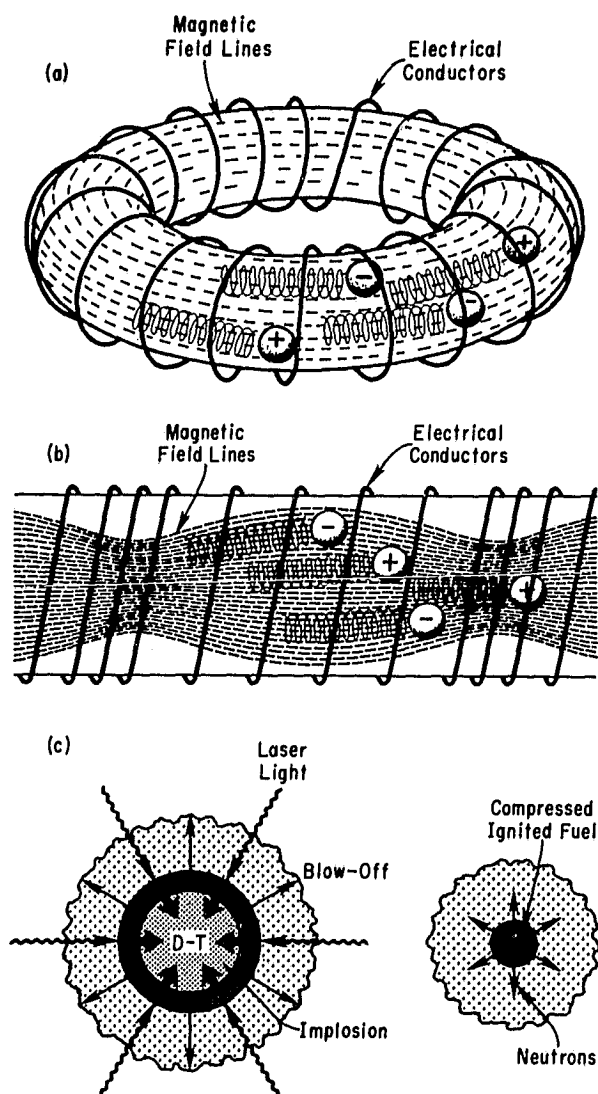


FIGURE 4.3 (a) Toroidal magnetic confinement. Charged particles gyrate in tight spirals about closed magnetic field lines, passing time and time again around the doughnut-shaped containment vessel. (b) Mirror magnetic confinement. The magnetic field lines are open, but charged particles are reflected at high-field regions at the ends of the device and thus remain trapped within the containment vessel. (c) Inertial confinement. A tiny D-T pellet is imploded by high-power laser light to a density high enough for thermonuclear burn to occur.

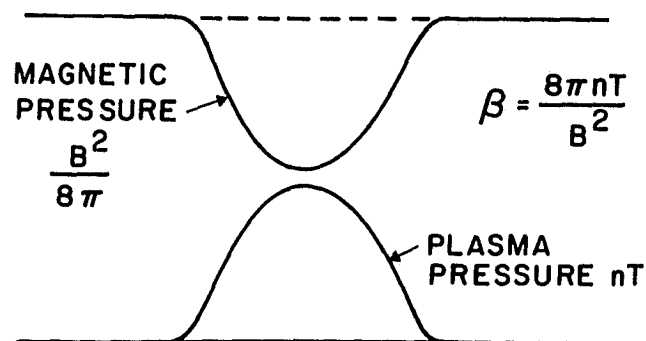


FIGURE 4.4 Illustration of the depression in the magnetic pressure  $B^2/8\pi$  caused by the kinetic pressure  $nT$  of a confined plasma. Here,  $B$  is the field strength,  $n$  the density of electrons and ions, and  $T$  the plasma temperature. The ratio of the two pressures is  $\beta = 8\pi nT/B^2$ .

reactor economics by better utilization of the magnetic energy, which can result either in reduced requirements on field strength or in a more compact reactor configuration; in the latter case, however, the higher fusion power density can represent a formidable engineering problem.

The various magnetic bottles that are possible candidates for confining a fusion plasma divide into two main classes: toroidal (doughnut-shaped) configurations, illustrated in Figure 4.3(a), and mirror (linear, narrowing at the ends) configurations, illustrated in Figure 4.3(b). Toroidal magnetic configurations have the special advantage that charged particles cannot escape by simply moving along the magnetic field lines. Moreover, when ions collide with each other, they are deflected only one radius of gyration across the confining field. Many such collisions will, of course, lead to a slow migration (diffusion) of ion energy to the walls of the containing vessel. In order to minimize the importance of this particular energy-diffusion process as an obstacle to the achievement of fusion conditions, it is sufficient that the minor radius of the plasma torus should be more than a hundred times larger than the radius of gyration, that is, about 1 m or greater.

One of the simplest of the toroidal configurations—the tokamak—has been by far the most successful of all fusion concepts in realizing reactorlike plasma conditions in laboratory-size experiments and has already come within a factor of 4-5 of meeting minimum break-even requirements. The tokamak, and its close cousin the stellarator, are discussed later in this chapter.

The principal alternative approach to a fusion reactor based on magnetic confinement is the mirror machine, an open-ended magnetic

bottle in which most, but not all, ions are prevented from escaping along field lines by an increase in the magnetic intensity at the ends of the device. The energy confinement times are then determined by particle collisions, which scatter the ion velocity vectors into the loss regions. Mirror-confinement concepts are also discussed later in this chapter.

A number of alternative toroidal configurations—the bumpy torus, which adds high-energy mirror-confined electrons to produce a moderate-beta steady-state toroidal plasma; the reversed-field pinch, which produces a very-high-beta pulsed toroidal plasma; and the compact torus, which produces a moderate-beta plasma without any external magnetic coils linking the plasma—have become important elements in the U.S. program and are also discussed below.

In striving to attain the prescribed range of reactorlike parameters, experiments on magnetically confined plasmas have encountered four main energy-loss processes, listed here in order of increasing severity, that must be kept under control: (i) particle collisions, which disrupt the orbits of confined particles and give rise to an irreducible rate of diffusive energy loss; (ii) radiative cooling of the plasma, mainly in the form of ultraviolet radiation from impurity ions; (iii) fine-scale plasma instabilities, in effect tiny stepwise particle migrations that allow plasma energy to diffuse gradually across the magnetic field lines to the walls of the containing vessel; and (iv) large-scale plasma instabilities, that is, spontaneous deformations of the confining field that cause the plasma to escape abruptly out of the magnetic bottle. Although these four energy-loss processes take different forms in different magnetic configurations, progress in research on both toroidal and mirror-confinement concepts has been paced by a gradual improvement in the understanding of the fundamental physical mechanisms underlying all four processes and by the development of effective techniques to minimize them. However, the quest for a more complete, fundamental understanding of these processes still presents the science of plasma confinement with its most difficult and challenging problems.

Although the stability and transport of magnetically confined plasmas tend to be quite sensitive to the shape of the magnetic bottle, the various techniques that have been developed for heating a confined plasma tend to be applicable in a wide variety of magnetic configurations. A number of confined plasmas—notably tokamaks—are subject to one intrinsic type of heating, which arises from the resistive dissipation of the plasma currents that are needed to maintain plasma equilibrium. Because of the rapid decrease in plasma resistivity with increasing electron temperature, this type of intrinsic heating is gener-

ally inadequate to heat a plasma to fusion temperatures, except in some high-current-density toroidal pinch configurations. The auxiliary heating power (that is, the power in addition to the intrinsic heating by the plasma current) that will be required to heat a plasma to fusion conditions can be estimated by noting that a deuterium-tritium plasma with a pressure of 6 atmospheres produces a fusion power density of about  $5 \text{ MW/m}^3$ , corresponding to an alpha-particle heating power density of about  $1 \text{ MW/m}^3$ . An auxiliary-heating power density of about half this value is found to be needed to heat an initially cold plasma to temperatures at which self-heating by fusion reactions becomes important. Thus, to heat a reactor plasma with a volume of order  $100 \text{ m}^3$ , a total heating power of order 50 MW will be needed. Present-day experiments operate with auxiliary heating powers typically of up to about 10 MW.

One of the most effective plasma-heating techniques has been the injection into the plasma of intense beams of energetic neutral atoms of hydrogen or deuterium. These freely cross the confining magnetic field until they are stripped of their electrons, by collisional ionization and charge exchange, and are then retained in the plasma as energetic ions, gradually transferring their energy to background plasma particles by collisions. As an alternative to this type of neutral-beam heating, a variety of radio-frequency electromagnetic waves can be launched into a magnetically confined plasma, and there are a number of resonant frequencies at which such waves are strongly absorbed by the plasma, their energy being converted into thermal energy of the plasma particles. These radio-frequency heating processes have been known theoretically since the earliest days of plasma research, but only in recent years have they been applied successfully to heat plasmas to fusion temperatures. Plasma heating techniques—both neutral-beam and radio-frequency—are discussed later in this chapter.

### **Inertial Confinement**

Separate from all the magnetic-confinement concepts, there are a number of entirely different inertial-confinement schemes, in which intense beams of laser light or accelerated particles are focused onto the surface of a tiny pellet filled with deuterium-tritium fuel [see Figure 4.3(c)]. The pellet implodes because of the rocketlike reaction to the blow-off of the surface material of the pellet by deposition of the beam energy; as a consequence, the density rises to extremely high values ( $10^{25}$  particles per cubic centimeter, about a thousand times solid densities). The fuel heats up because of compression and shock waves,

and fusion temperatures are produced in the center of the pellet; thermonuclear ignition then occurs. If the yield of this miniature thermonuclear explosion is high enough, the fusion energy can be used for several applications, including power generation.

Inertial-confinement fusion differs from magnetic fusion in that plasma confinement is provided by the inertia of the exploding pellet, not by a magnetic bottle. A key parameter in inertial fusion, equivalent to the confinement (Lawson) parameter in magnetic fusion, is the product of the density and radius of the compressed pellet. For inertial fusion to work, this parameter must be large enough for the fusion products to be contained, thus allowing propagating thermonuclear burn. Density compression is required to increase the rate of fusion reactions during the brief instant (less than  $10^{-9}$  s) that inertia holds the pellet together.

Very stringent physics requirements must be satisfied in order to achieve the ultra-high-density compressions and thermonuclear temperatures needed for ignition with a reasonably sized beam driver. First, the incident beam energy must be absorbed efficiently at the pellet surface. Second, in order to achieve highly compressed fuel volumes, the symmetry of implosion must be excellent, and the fuel temperature must remain as low as possible until the instant of ignition. Finally, there must be satisfactory means of igniting the imploded pellet at the right moment—implying a good pellet design.

Research in inertial fusion is aimed at elucidating the physics that dominates the behavior of the driver-pellet interaction, especially for laser drivers. The physics of the coupling of driver energy to the pellet has been a preeminent issue, because the partition of beam energy in the pellet determines whether the physical requirements for fusion can be met. Lasers have been the drivers used for almost all inertial fusion research to date, because their high-power beams can be focused to the intensities needed for inertial fusion. [Both neodymium-glass lasers, which operate with a wavelength of 1  $\mu\text{m}$ , and  $\text{CO}_2$ -gas lasers, with a 10- $\mu\text{m}$  wavelength, with outputs of up to 100 kilojoules (kJ) have been developed for inertial-confinement fusion experiments.]

As an alternative to lasers, intense particle beams can be used as drivers—either light-ion beams or heavy-ion beams. The light ions are generated in high-current pulsed-power accelerators that provide megaamperes of ion current at a few megavolts energy; these generators are highly efficient and relatively inexpensive but cannot as yet attain the power densities required for fusion, although the technology is rapidly improving. The heavy-ion-beam approach would use ions such as uranium accelerated to gigaelectron-volt energies in conven-

tional accelerators; the accelerators needed to generate the heavy-ion beams would be expensive but would have many properties desirable for inertial fusion applications.

Steady progress has been made toward the achievement of fusion by inertial confinement. Pellets have been compressed to a hundred times solid density, fusion temperatures have been reached, and remarkable advances have been made in driver technology. However, much further progress needs to be made to satisfy simultaneously all the requirements for the practical realization of fusion power. Inertial-confinement fusion is discussed toward the end of this chapter.

## **TOKAMAK AND STELLARATOR MAGNETIC-CONFINEMENT SYSTEMS**

### **Introduction**

- Closed field-line magnetic-confinement systems of the tokamak and stellarator type have displayed a sustained favorable trend in experimental achievements, and tokamaks now occupy the dominant position in fusion research worldwide.

The tokamak and stellarator are magnetic-confinement devices utilizing closed magnetic fields and toroidal (doughnut-shaped) plasmas. The main magnetic field is produced by external coils. Although the simplest toroidal magnetic field [Figure 4.5(a)] does not confine plasma, a twisted toroidal field does [Figures 4.5(b)-4.5(d)].

The tokamak, which has a symmetric toroidal plasma, has an additional magnetic field produced by a current flowing in the plasma. This additional field gives the required twist [Figure 4.5(b)].

The stellarator is not symmetric around the torus, which allows the twist in the magnetic field to be produced by external coils, with no plasma current [Figures 4.5(c) and 4.5(d)].

The early development of the tokamak took place in the Soviet Union, but the concept has played an increasingly important role in the U.S. and world fusion programs since the late 1960s. It was the simplicity of the tokamak, in which the plasma current provides not only good confinement but also creates and heats the plasma, that first led to its choice as the centerpiece of many fusion research programs worldwide. A sustained favorable trend in tokamak experimental results has led to the tokamak's becoming the largest element in the U.S. program and dominating the fusion programs of Europe and Japan.

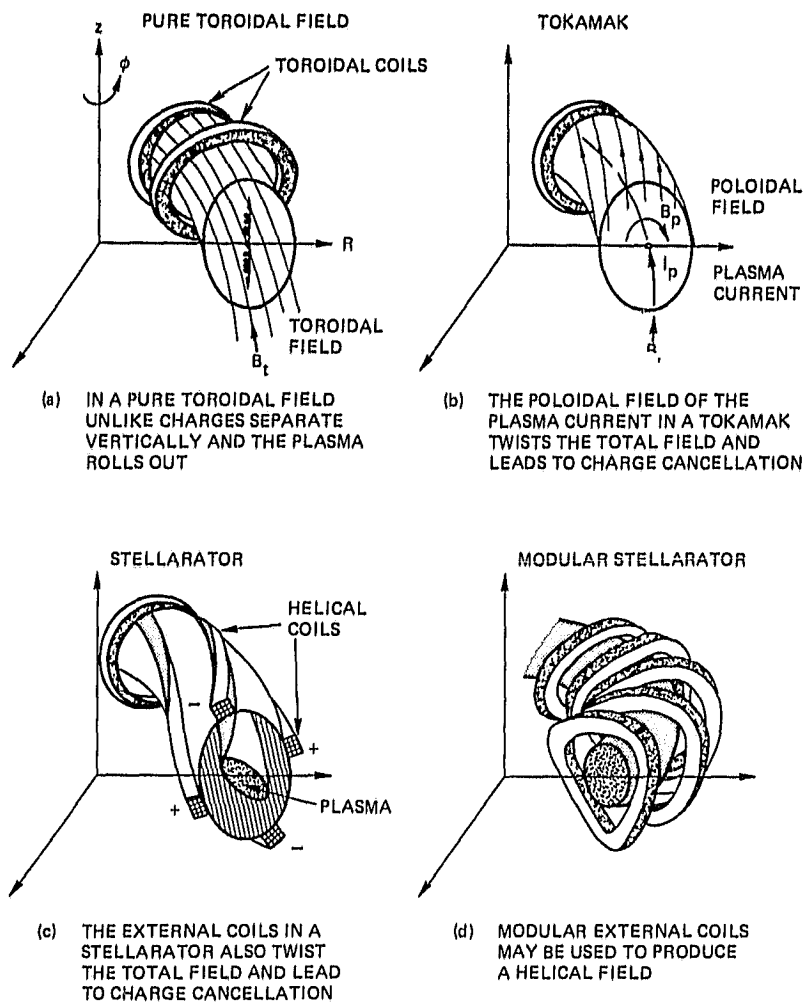


FIGURE 4.5 Toroidal confinement systems—pure toroidal field (unable to confine plasma), tokamak, stellarator, and modular stellarator.



Tokamak experiments have already obtained plasma parameters close to those required in a reactor. Indeed, experiments just coming into operation, the Tokamak Fusion Test Reactor (TFTR) at Princeton, New Jersey, and the Joint European Torus (JET) in Europe, should produce more thermonuclear power than the power required to heat the plasma.

The stellarator concept originated at Princeton in the early 1950s, but stellarator research was almost totally displaced in the United States

TABLE 4.1 Representative Tokamaks<sup>a</sup>

Device	Location	(m)	(cm)	Magnetic Field Strength (kG)	Plasma Current (MA)	Pulse Length (s)	Program Contributions <sup>c</sup>
Alcator A	GA	1.7	82	22	3.5	10	(S,B,PD,RF)
TFTR	PPPL	2.5	85	52	2.5	2	C,DT,NB,PW,RF
DIH	GA	1.4	58 <sup>d</sup>	40	2.5 <sup>d</sup>	1	S,B,PD,NB
ALCATOR C	MIT	0.6	17	140	1.0	1	C,RF,CD
PLT	PPPL	1.3	45	35	0.6	3	C,NB,RF,CD
PDX	PPPL	1.4	45	24	0.5	1	PD,NB,S,B
TEXT	Texas	1.0	28	30	0.4	0.5	C,RF
ISX-B	ORNL	0.9	37	18	0.3	0.3	B,F,S,C
Macrotron	UCLA	0.9	40	4	0.1	0.1	RF,PW,C
Torus II	Columbia	0.2	9	5	0.1	10 <sup>-5</sup>	B
Tokapole	Wisc.	0.5	22	1	0.1	10 <sup>-2</sup>	C,RF,PD
JET	EEC	2.9	160	35	4.8	20	C,DT,NB,RF,PW
JT-60	Japan	3.0	100	45	2.7	10	C,NB,RF,PD
T-15	USSR	2.4	70	45	2.0	1+	(SC,C,NB,RF)
ASDEX-U	FRG	1.6	50	39	2.0	6	(PD,C,B,PW)
Tore-Supra	France	2.1	70	45	1.7	30	(SC,RF,CD)
FT	Italy	0.8	19	100	1.0	1	C,RF
TFR-600	France	1.0	20	60	0.6	1	C,RF
ASDEX	FRG	1.6	40	28	0.5	10	PD,PW,C,B
T-10	USSR	1.5	37	30	0.5	1	C,RF
JFT-2M	Japan	1.3	45	15	0.5	1	B,NB,RF
TEXTOR	FRG	1.7	50	26	0.5	3	PW
JIPP T-II	Japan	0.9	25	20	0.3	0.3	TS,RF,F
DITE	UK	1.2	28	27	0.3	0.5	BD,F,NB,PW
T-7	USSR	1.2	31	24	0.2	1	SC,CD
JFT-2	Japan	0.9	16	20	0.3	0.3	B,NB,RF

<sup>a</sup> Listed in descending magnitude of plasma current, with U.S. devices listed first.

<sup>b</sup> Average minor radius in the case of noncircular cross-section devices.

<sup>c</sup> Program contributions in parentheses for devices still under construction. See Table 4.2 for key to program contribution codes.

<sup>d</sup> Parameters for a single lobe of the doublet configuration.

by the tokamak, starting in 1969. Recently, there has been a considerable revival of interest in the stellarator. This is due, in large part, to exciting experimental results from stellarators in Germany and Japan. A larger stellarator effort is now under way in the United States, with the goal of demonstrating a conceptual improvement in toroidal systems.

The parameters and research areas of representative tokamaks and stellarators are shown in Tables 4.1 and 4.2, respectively. These tables illustrate well the international character of, and contributions to, tokamak and stellarator research and the key part played by the U.S. program. In the United States, work is concentrated at GA Technologies Inc. (formerly General Atomic), La Jolla, California; the Massachusetts Institute of Technology, Cambridge, Massachusetts; the Oak Ridge National Laboratory, Oak Ridge, Tennessee; and the Princeton Plasma Physics Laboratory, Princeton, New Jersey; with the Princeton laboratory playing a lead role in the program. Substantial supporting work is undertaken in universities such as the University of Texas at Austin; Columbia University; New York University; the University of California, Los Angeles; and the University of Wisconsin.

TABLE 4.2 Representative Stellarators<sup>a</sup>

Device	Location	Major Radius (m)	Minor Radius <sup>b</sup> (cm)	Field Strength (kG)	Rotational Transform <sup>c</sup>	Pulse Length (s)	Program Contributions <sup>d</sup>
ATF-1	ORNL	2.1	30	20	0.95	5	(T,TS,C,B,NB,RF)
IMS	Wisc.	0.4	5	6	0.6	0.1	MST,C
WVII-AS	FRG	2.0	20	30	0.4	1	(MST,C,B,NB)
Heliotron	Japan	2.2	20	20	2.1	1	T,TS,C,NB,RF
Uragan-3	USSR	1.0	16	30	0.7	0.5	T,C,RF
L-2	USSR	1.0	12	20	0.7	0.3	S,TS,C,RF
W VII-A	FRG	2.0	10	25	0.2	1	S,TS,C,B,NB

<sup>a</sup> Listed in descending magnitude of minor radius, with U.S. devices listed first.

<sup>b</sup> Average minor radius.

<sup>c</sup> Rotational transform is the number of times a field line circuits the poloidal circumference in one complete circuit of the toroidal circumference.

<sup>d</sup> Program contribution codes for Tables 4.1 and 4.2 are as follows: confinement (C), high-beta (B), shaped plasma (S), neutral-beam heating (NB), radio-frequency heating (RF), poloidal divertor (PD), bundle divertor (BD), plasma-wall interactions (PW), fueling (F), operation with tritium (DT), superconducting coils (SC), stellarator (S), torsatron (T), tokamak-stellarator hybrid (TS), modular stellarator (MST).

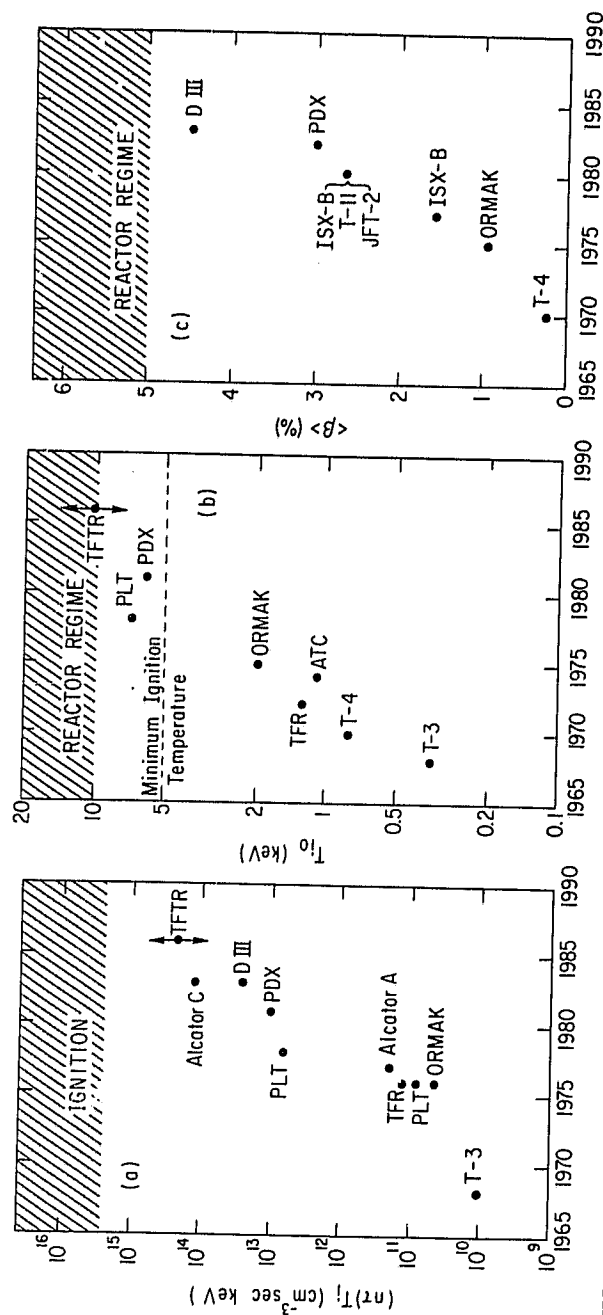


FIGURE 4.6 Progress in tokamak plasma parameters. (a) Experimentally achieved values of the ignition parameter  $n\tau T_i$ , where  $n$  is the plasma density,  $T_i$  is the ion temperature, and  $\tau$  is the energy confinement time. (b) Values of central ion temperature  $T_{i0}$ . (c) Values of volume-averaged  $\beta$  in percent. The plasma cross section in DIII at GA Technologies, Inc., is elongated and D-shaped; the cross sections in the other tokamaks are approximately circular.

### Major Advances

- Tokamak plasma parameters are approaching reactor requirements; stellarators behave as well as tokamaks of comparable size.

For more than 30 years, the improvement in experimental capabilities and physical understanding of toroidal plasmas has been remarkably steady. The advances of the last decade have brought us to a point at which ignited fusion experiments can be designed with confidence and have been based on the solid foundations of toroidal plasma physics built in the 1950s and 1960s.

The most impressive experimental achievements have been in tokamak research, where a number of critical plasma parameters have improved dramatically during the past decade. Possibly the most critical parameter is the product of density, ion temperature, and energy confinement time, which measures the approach to reactor conditions. This parameter has increased by a factor of more than a hundred in the past decade, although another factor of just less than a hundred is still required for ignition [Figure 4.6(a)]. Reactorlike ion temperatures have already been achieved [Figure 4.6(b)], and the plasma beta needed in an ignited reactor has been approached [Figure 4.6(c)].

The present experimental achievements are, however, mainly in separate devices, each with specialized characteristics. In the next phase of the program, experiments such as TFTR, JET, and other devices in the U.S. and world programs will work toward the goal of achieving simultaneously all the needed reactor-grade parameters.

The stellarator has also made substantial progress, although stellarators generally lag behind tokamaks in size by a few years. Nevertheless, stellarator plasmas are found to have characteristics comparable with those of tokamaks of similar size.

### OPTIMIZATION OF EXPERIMENTAL PERFORMANCE

- The development of powerful auxiliary heating, coupled with improved techniques for plasma control, has been the key to the realization of reactorlike plasma parameters. Demonstrations of the efficacy of magnetic divertors for impurity control, and of steady-state transformer-free current drive, have further improved the prospects of the tokamak as a viable reactor candidate.

The substantial improvements in the basic plasma parameters of tokamaks and stellarators have been partly due to increased plasma

size and partly due to the successful implementation of several auxiliary techniques for optimizing plasma performance. These techniques have taken a number of different forms: (i) magnetic shaping and feedback control of the plasma cross section; (ii) programmed density variation by controlled addition of gas (puffing) and by injection of solid hydrogen pellets; (iii) auxiliary plasma heating (additional to the intrinsic heating from the plasma current) by injection of intense beams of energetic neutral atoms, by radio-frequency electromagnetic waves, and by adiabatic compression; and (iv) control of the plasma edge conditions by specially designed mechanical "limiters," by suitable choices of limiter and wall materials, and by "magnetic divertors."

In the early 1970s, the four main tokamaks in the United States were the ST and ATC devices at Princeton, ORMAK at Oak Ridge, and Doublet II at General Atomic, which had auxiliary heating powers up to a few hundred kilowatts (comparable with the heating by the plasma current) and pulse lengths of a few hundred milliseconds. The best plasma parameters achieved were as follows: central ion and electron temperatures of up to 2 keV; confinement parameter (product of density and confinement time) of up to  $3 \times 10^{11}$  particles per cubic centimeter seconds; and plasma beta as high as 1 percent.

By the late 1970s, these devices had been replaced by larger experiments, with auxiliary heating powers in the multimewatt range and pulse lengths typically of 1 s. These larger experiments, mostly still in operation, are the PLT and PDX tokamaks at Princeton, ISX at Oak Ridge, Doublet III at GA Technologies, and Alcator A and C at the Massachusetts Institute of Technology. These experiments also have better access for diagnostics and heating, improved plasma-shaping capability, and various types of active impurity and particle-control systems. The best plasma parameters achieved have been as follows: central ion temperature of up to 7 keV; central electron temperature of up to 4 keV (both in PLT); confinement parameter of up to  $8 \times 10^{13}$  particles per cubic centimeter seconds (Alcator C); and plasma beta of up to 4.5 percent (Doublet III).

In a tokamak, the plasma current is necessary for confinement, and it also provides the initial heating of the plasma. Technically, the simplest way to produce the required plasma current is to make the plasma the output circuit (secondary winding) of a transformer. Unfortunately, a transformer can drive current in one direction for only a limited time. In a tokamak reactor, the transformer could drive the current for as long as a few hours in a single pulse. Nevertheless, it would be desirable to be able to operate for longer pulses, or even in steady state. Based on earlier theoretical studies, it has been shown

both in Alcator C and in PLT that substantial plasma currents may be driven using electromagnetic waves of appropriate frequency (see section on Radio-Frequency Current Drive).

Part of the renewed interest in stellarators stems from their virtue of having no net plasma current. The pure stellarator, in which all the fields are supplied by currents in external coils, is therefore inherently steady state.

The successful suppression of impurities has been a major factor in the success of tokamaks. Impurities are generated in a tokamak because of the interaction of the plasma edge with the walls of the confining vessel. Conventionally, the plasma edge in a tokamak is defined by a solid object, called a limiter; considerable advances have been made in choosing a material for the limiter that minimizes impurities. Alternatively, the plasma edge is defined by a divertor, which uses special magnetic fields to isolate the plasma from the vessel walls. Divertors reduce impurity contamination by (i) depositing heat from the plasma on a distant target plate, (ii) preventing the backflow of impurities to the plasma from the target plate, and (iii) shielding the plasma from wall-generated impurities. There have been a number of successful divertor experiments in the United States and abroad. A significant development for particle control has also been the extension of the intrinsically simpler limiter technique to provide pumping at the limiter—a concept known as the pumped limiter.

The understanding of tokamaks and stellarators has been improved by the development of an impressive battery of plasma diagnostics. These diagnostics, coupled with computer-aided data-acquisition and -analysis systems, have made it possible to make accurate tests of theoretical models and to establish well-tested empirical models of plasma behavior. These models have been used in computer codes that simulate plasma behavior in considerable detail and that can be used to predict results in future large tokamaks.

#### CONFINEMENT

- Toroidal systems have the potential for very favorable plasma confinement, if classical-like processes prevail. In tokamaks, anomalous processes of electron loss arise that, while not thoroughly understood from a fundamental viewpoint, are found to obey empirical laws that scale favorably with increasing plasma size. Nearly classical ion confinement has been observed in many tokamak experiments. In stellarators, classical-like processes of

ion loss are more severe but are predicted to be manageable in a reactor-size device.

The variation in magnetic-field strength on a surface of constant pressure in toroidal devices causes particles to drift across these surfaces. For particles moving parallel to the field, the projected orbit on a minor cross section of the plasma is a circle displaced slightly from a surface of constant pressure. Particles with greater perpendicular motion may be reflected from regions of higher magnetic-field strength. In tokamaks, this latter class of trapped particles has orbits that project onto the minor cross section into the characteristic "banana orbits" shown in Figure 4.7. Thus, the radial excursion of a particle exceeds the basic gyroradius with which particles spiral about a field line, and

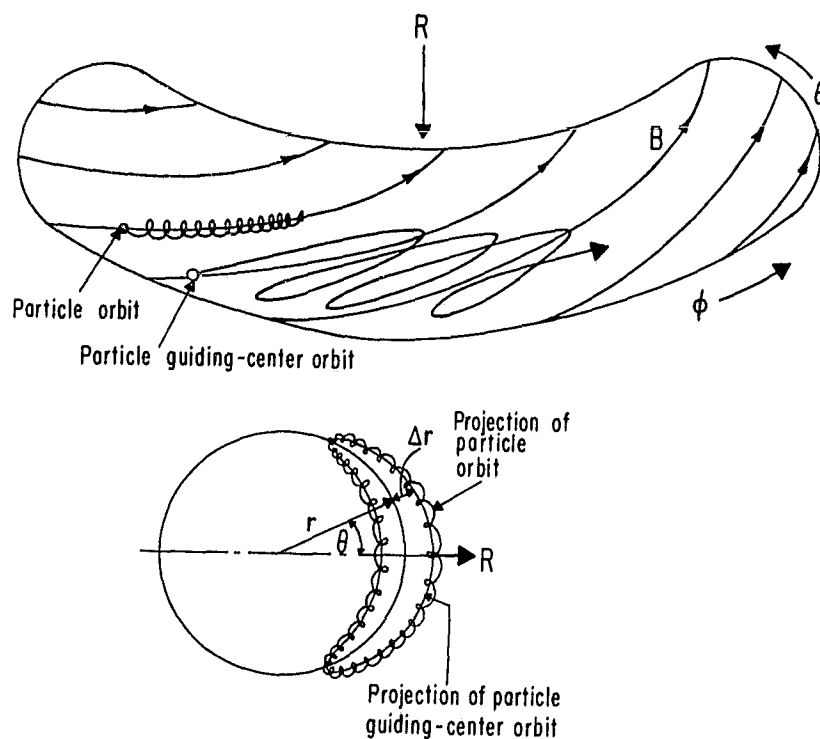


FIGURE 4.7 Trapped-particle orbits in a tokamak. A trapped particle gyrates in tight spirals about a magnetic field line, while bouncing back and forth along the field line and slowly precessing around the torus. The projection of the particle's orbit onto a cross-sectional plane is a closed orbit in the shape of a banana.

this leads to an increased radial step following each interparticle collision and to increased diffusion and heat conduction. The theory of confinement that includes these orbit effects is termed "neoclassical." In a fusion-grade plasma, a typical particle will travel around the torus many thousands of times between collisions, with the consequence that neoclassical transport should be quite small.

With the advent of substantial auxiliary heating in tokamaks, it has been possible to vary plasma parameters considerably and to measure the ion thermal conductivity over a wide range of collisionality. In almost all cases, the ion thermal conductivity is close to neoclassical predictions. This is particularly encouraging since, at low collisionality, it had been predicted theoretically that new types of plasma fluctuations could arise that would degrade ion confinement.

The neoclassical confinement is degraded when the symmetry of the toroidal configuration is broken, since the banana orbits no longer have a closed projection as they do in Figure 4.7. This effect occurs in stellarators owing to the intrinsic lack of toroidal symmetry. Trapping of ions occurs in the helical troughs in the field strength and is predicted to lead to losses at low collisionality enhanced over those of a symmetric toroidal plasma. These losses may be substantially reduced by radial electric fields set up by the plasma to maintain charge neutrality. This is an active area of current research, and the theory of confinement in asymmetric plasmas has advanced considerably in the last decade. Codes based on the Monte Carlo method for following the dynamics of a large number of particles have allowed calculations to be made for magnetic-field configurations that are accurate representations of actual experimental situations. The outlook for ion confinement in stellarators has improved considerably as a result of these recent more sophisticated calculations.

In sharp contrast to the situation with ion confinement, electron confinement in tokamaks is found to be degraded from the neoclassical level, resulting in so-called anomalous transport. However, since electron neoclassical confinement would be substantially better than ion neoclassical confinement, quite large anomaly factors can be tolerated in electron losses before these exceed the ion losses.

A key study of electron confinement was undertaken in the Alcator A tokamak. By virtue of the high toroidal-field capability of this device (up to 100 kG) and high plasma current density, it was possible to vary the plasma density over a wide range. It was found that the electron thermal diffusivity (the rate at which energy is transported by the electron component diffuses to the vessel wall) is proportional to the electron density. Similar behavior is observed in other tokamaks.



heated by the plasma current alone. This led to an empirical confinement scaling that was diffusive in nature, that is, the confinement time increased with the square of the minor radius of the plasma and with the plasma density. This empirical scaling, coupled with the favorable ion-confinement scaling, indicates that ignited tokamak plasmas may be obtained in devices only slightly larger than the new generation of large tokamaks, namely TFTR and JET. More recent data from Alcator C, in which the plasma minor and major radii were varied, suggests a somewhat modified empirical scaling, but with an even more favorable dependence on overall plasma size, namely that the confinement increases only linearly with plasma minor radius, but also increases with the square of the major radius.

When intense additional heating is applied to a tokamak plasma, the electron energy confinement is often degraded relative to the case with current heating alone. This degradation may be a direct result of differences in heating techniques, or it may be due to increases in plasma beta. The scaling of energy confinement is also quite different: confinement is found to be relatively insensitive to plasma density but increases with the strength of the poloidal magnetic field and with the square of the plasma minor or major radius. This scaling also predicts that ignition would be achievable in devices modestly larger than TFTR and JET.

A possible explanation of the degraded electron confinement may lie in small-scale plasma fluctuations, so called microinstabilities. Density fluctuations have been measured whose wavelengths and frequencies correspond well to theoretical predictions. However, while theory can predict the possible existence of such fluctuations, a fully self-consistent theoretical treatment predicting fluctuation amplitudes and their relationship to confinement is beyond our present capabilities.

In a stellarator, anomalous electron behavior occurs when a plasma current is used to initiate and maintain the plasma. Improved electron confinement, however, occurs in both the German (WVII-A) and Japanese (Heliotron E) stellarators when auxiliary heating is used and the current is turned off.

#### STABILITY AND BETA LIMITS

- Stable plasma betas approaching 5 percent have been demonstrated in tokamaks; detailed theoretical analyses of stability against current-driven kink modes and pressure-driven ballooning modes indicate that significant further advances in beta should be

possible. Stellarators are also predicted to have beta limits in the 5-10 percent range.

On the macroscopic scale, a toroidal plasma may be treated as a perfectly conducting fluid. This model is used to establish self-consistent toroidal equilibria, plasma pressure profiles, and internal and external magnetic fields. The stability of these equilibria is examined by studying the growth of characteristic perturbations of the plasma. Lack of stability frequently means that the plasma merely assumes a small helical distortion—usually seen as a rotating distortion in the experiments—but, in a severe case, it can result in a catastrophic loss of confinement.

In a perfectly conducting (ideal) plasma, the plasma and the magnetic field are locked together. The finite resistivity of a real plasma permits the plasma and magnetic fields to rearrange themselves. In practice, finite-resistivity effects are only important on pressure surfaces where a helical distortion of the plasma twists in resonance with the helical magnetic field, thereby facilitating this kind of field rearrangement. These resonances cause the constant-pressure surfaces to break up, leading to the formation of localized magnetic structures called magnetic islands. Helical distortions of the plasma can be induced either by a gradient in the plasma current density, and are then usually called kink or tearing modes, or by the pressure gradient, in which case they are usually called interchange or ballooning modes.

Tearing modes play an important role in the behavior of tokamak plasmas. The helical twist of the magnetic field is measured by the safety factor, which is the number of times a field line circles toroidally while encircling the plasma once the short way around. The safety factor in a tokamak increases from the center of the plasma to the plasma edge. If the safety factor is significantly less than unity in the center of a tokamak, there is always an unstable tearing mode. This mode is frequently seen as a variation of the x-ray emission from the plasma center; it limits the central density and temperature but is otherwise relatively harmless. If the current profile is not properly controlled, higher-order tearing modes can arise, which can interact with each other to give a sudden loss of plasma confinement, called a disruption. When careful control is exercised over the plasma, this phenomenon may be avoided. Pure stellarators have no current and are free of disruptions and other current-driven instabilities.

Ballooning modes are small corrugations of the pressure surfaces that follow the twist of the field lines. These distortions are caused by the plasma pressure gradient and therefore occur when the plasma beta

is raised above a critical value. The effect of these distortions on confinement is not fully understood. However, the presumption is that if the confinement is sufficiently degraded that these modes set an upper limit on the obtainable value of beta.

Theoretically, the ballooning-mode limit on beta for a circular cross-section plasma is about 3 percent. For elongated (in particular, D-shaped) cross-section plasmas, this limit may be increased to 7 percent for a plasma of aspect ratio (ratio of major to minor radius) of about 3. Current research indicates that even higher beta values may be possible with other plasma cross sections. In a number of experiments with circular plasmas (ISX-B, PDX, Doublet III, as well as several foreign tokamaks), beta has been raised to around 3 percent. In a noncircular plasma, Doublet III has achieved a beta of 4.5 percent. However, as beta is raised, these devices have generally experienced a degradation of electron confinement. Detailed fluctuation studies in ISX-B suggest that this degradation may result from finite-resistivity ballooning modes. Fortunately, such effects should diminish in larger, higher-electron-temperature plasmas.

The theoretical understanding of ballooning and tearing modes has seen major improvements during the past decade. Large computer codes have been developed that provide the complete range of unstable modes and permit a detailed comparison between theoretical models and experimental measurements. In particular, these codes have provided definitive results on theoretical beta limits and, coupled with better diagnosed experiments, have given a detailed picture of the disruption phenomenon.

#### **Current Frontiers of Research**

- A new generation of tokamak facilities is coming into operation worldwide, with the capability of producing reactorlike confinement parameters and reactor-grade hydrogen and (deuterium-tritium) D-T plasmas. Results from these devices, together with information on beta optimization, impurity control, current-drive, and long-pulse plasma technology from several moderate-size specialized devices, should enable the tokamak program to embark on a major next step—a long-pulse ignition experiment. A new generation of moderate-size stellarator experiments is dedicated to configuration optimization, with a view to realizing fundamental improvements in toroidal confinement concepts.

The next phase of toroidal research will be centered around powerful

new facilities that are just now beginning operation or that are under construction for operation in the mid-1980s. New-generation tokamak devices such as TFTR, JET, the Japanese device JT-60, and an upgrade of the Doublet III device called DIII-D, have plasmas of about a meter in minor radius, multimegaampere current capability, pulse lengths of up to 10 s, and tens of megawatts of auxiliary heating. Moreover, TFTR and JET will eventually operate with D-T plasmas and should produce more thermonuclear power than is required to heat the plasma. In addition, several modest-scale devices will study improvements to toroidal confinement in the areas of steady-state operation, higher-beta operation, disruption control, and simplified impurity control. The goals of this phase of the program are the following:

- To study confinement at low collisionality and high beta in hydrogen and D-T reactor-grade plasmas,
- To study plasma behavior for longer pulse lengths,
- To develop advanced toroidal confinement concepts that can lead to more attractive reactor configurations.

It is expected that this phase will provide the technical foundation for the next step in the tokamak program, namely a device that will operate with an ignited D-T plasma during a long-pulse equilibrium to provide for the study of a plasma heated by fusion alpha-particles.

The key issue for tokamaks remains electron confinement. A vigorous program is under way to develop a predictive capability for anomalous transport, although the large plasmas of TFTR, DIII-D, JET, and JT-60 will be so close to reactor conditions as to require only a limited further extrapolation to reactor-scale plasmas. The diversity of configurations (circular, D-shaped, divertor) and heating techniques (neutral-beam and radio-frequency) to be found in this new generation of tokamaks offers the hope not only of optimization of experimental results but also of further progress toward an understanding of the underlying physics. TFTR and JET will also begin the study of fusion alpha-particle physics.

In the stellarator area, improvements of existing experiments (Heliotron-E, WVII-A) and new facilities that are under construction (WVII-AS in Germany and ATF-1 at Oak Ridge) will permit the study of high-beta and low-collisionality stellarator plasmas. The central issues are the role of the radial electric field, which maintains equal ion and electron losses, the effects of the helical magnetic ripple at low collisionality (high temperature), and possible degradation of confinement as beta is raised above a critical value.

In the past, most tokamak and stellarator reactor designs have been based on a plasma operating at a 3 to 7 percent beta level. Some years ago, it was predicted that, while unstable modes might set a limit on beta in a tokamak at about this level, nevertheless there would be a regime at even higher beta that would be stable—the so-called second stability regime. In a small tokamak, Torus II at Columbia University, transient plasmas have been set up with betas of around 12 percent using rapid heating. This augers well for the theory, but in larger devices the level of heating required to cross the unstable gap may be too large. Fortunately, some stable routes to the second stability regime have been identified. For tokamaks, the use of a kidney-bean-shaped plasma cross section, where the indentation of the bean is on the small major radius side of the plasma, can give direct access to the second stability regime. Studies of such a plasma will be undertaken in a modification of the PDX tokamak (PBX). Because the production of such a cross section in a reactor might be difficult, a second possible route has been identified, namely, stabilization of the plasma using an energetic electron component. For stellarators, a configuration (ATF-1) has been identified that also has a stable route, theoretically, to the second stability regime. Stellarators with a helically displaced plasma have also been shown theoretically to have a capability for very high stable betas.

A substantial effort is under way to increase the pulse length of tokamaks by the application of long-pulse heating power and radio-frequency power for current drive. The present noninductive current-drive schemes in a tokamak have power efficiencies that are just adequate for a reactor. The first goal of the current-drive program is to test theoretical predictions in reactor-grade plasmas; the second goal is to explore improved current-drive schemes. Even at low efficiency, current drive may still make an important contribution. For example, it may be used to start and raise the plasma current, thereby freeing the transformer for use only in current maintenance. Initial tests of this idea are encouraging; it should enable a tokamak reactor to have a pulse length approaching a day.

Stellarators have inherent steady-state capability, because the fields are all produced by external coils. The main issue for stellarators, once configurations with good confinement and beta have been established, is to find a coil set that is reactor relevant from the viewpoint of construction and maintenance. Tokamak-stellarator hybrids are also being studied that combine the good features of both devices, namely, the simplicity, good confinement, and satisfactory beta of a tokamak

and the disruption-free operation and reduced current-drive requirements of a stellarator.

The problem of maintaining a pure plasma for very long pulses involves the minimization of impurity production and the active removal both of wall-generated impurities and of alpha particles produced by the fusion reactions. In the next phase of the program, this will be studied by operating plasmas for progressively longer pulses, initially of about 10-s duration and ultimately in steady state. Control of the density will be achieved by using a mixture of gas puffing and pellet injection, coupled with either a pumped limiter or a magnetic divertor to remove excess particles. The control of impurities is a more difficult matter. There are some favorable conditions under which the plasma edge is predicted to operate at low temperature, in which case the production of impurities by sputtering would be low. If such conditions are found in reactor-grade plasmas, then the pumped limiter will be a reactor-relevant solution for particle and impurity control. If, on the other hand, a greater level of active control of the plasma edge is required, then a magnetic divertor will be necessary.

#### Prospects for Future Advances

- Improvements already demonstrated on smaller-scale experiments should greatly improve toroidal reactor attractiveness.

The program described above should lead to the early test of an ignited long-pulse thermonuclear plasma in a new tokamak that is a modest scale-up from today's largest devices. Simultaneously, the program will be developing concepts for improved performance of toroidally confined plasmas in a wide range of areas:

- High beta operation with good confinement;
- Current drive:  
assisted start-up,  
plasma profile control,  
steady-state operation;
- Steady-state stellarator operation;
- Disruption-free operation; and
- Simplified particle and impurity control.

Each of these improvements will depend on further advances in theoretical analysis, in computer modeling, and in the diagnosis and analysis of experimental data. The ability to model the complete toroidal plasma system, coupled with the development of more-reliable

input in each constituent area, will lead to the identification of optimized toroidal configurations that combine the best features of all the proven advances.

Impurity control by means of poloidal divertors has been demonstrated successfully on PDX and will be pursued further in foreign tokamak programs. The advantages of high-beta bean-shaped plasmas are to be explored on the PBX modification of PDX. Techniques for quasi-steady-state operation, with emphasis on radio-frequency current drive, are being developed on Alcator C and PLT. Eventually, the program must address a variety of long-pulse physics, engineering, and technology issues in an integrated superconducting tokamak environment. The improvement of stability against transients by means of stellarator-type shaping features will be addressed by the ATF-1 torsatron device.

The principal advanced reactor candidates are the ultra-long-pulse tokamak using radio-frequency-assisted start-up, the steady-state tokamak using current drive, and a variety of stellarators. A number of routes to the high-beta second-stability regime have been identified, both in tokamaks and in stellarators. High-beta operation, that is, at levels well above the minimum reactor requirement, coupled with long pulse or steady state, should lead to extremely attractive reactor economics.

## MAGNETIC MIRROR SYSTEMS

### Introduction

- Fusion plasmas can be magnetically confined in an open-ended tube by strengthening the magnetic field at the ends of the tube to form magnetic mirrors. Open-ended systems possess some important advantages for fusion purposes.

In the principal alternative approach to magnetic confinement, an open system, the magnetic field lines leave the plasma at each end of a tubular-shaped confinement volume. Plasma escape along the open lines is inhibited by strengthening the magnetic intensity at the ends, creating the so-called mirrors. These magnetic mirrors turn back those particles whose spiraling motion along the field lines is not too nearly directed along the field, i.e., those whose velocity vector (pitch) angle does not lie within the loss cone with respect to the magnetic field. Particles trapped between the mirrors in this way will continue to bounce back and forth until their pitch angle is deflected into the loss

ory, showed that the rapid ionization results from collective electron heating by lower-hybrid plasma waves plus classical ionization. This effect is now thought important to rotating plasma devices such as centrifuges, the formation of minor bodies in the early solar system, comets, satellite-magnetosphere interactions, neutral-gas releases in space, and, possibly to the interaction of the Space Shuttle with the plasma through which it moves.

The critical ionization phenomenon was incorporated in models of millimeter-wave radio emission from molecules behind the shock waves observed in magnetized molecular clouds, the sites of star formation.

Chemical releases proved their worth in diagnosing the plasma flows and electric fields in the magnetosphere and in the auroral acceleration region.

#### SPACE AND ASTROPHYSICAL PLASMA PHYSICS IN THE NEXT 10 YEARS

We restrict ourselves to a general assessment of the state of our subject after the next 10 years. *We assume that currently planned programs will be carried to completion because they lay the necessary foundations for the next generation of space missions.*

The initial exploration of solar-system plasmas will have been nearly completed. In 1986, an international consortium of spacecraft will fly by comets Halley and Giacobini-Zinner and provide the first in situ measurements of any comet. The International Solar Polar Mission will study the solar wind, and its effects on cosmic rays, in three dimensions for the first time. A Voyager spacecraft will make the first in situ measurements of the magnetospheres of Uranus and Neptune. The Galileo mission will diagnose Jovian magnetospheric plasma as completely as any space plasma to date. A Pioneer or Voyager spacecraft might leave the heliosphere by the end of the decade and thus detect interstellar matter and galactic cosmic rays directly. In situ measurements of solar plasmas will be the primary unexplored problem in solar-system plasma research.

The plasma environment of the Earth will be subjected to controlled study and, perhaps, to a measure of control, through the systematic use of active experiments and by synoptic measurements provided by the International Solar-Terrestrial Program.

High-resolution optical measurements, by the Solar Optical Telescope, and radio observations, by the Very Large Array and by very-long-baseline interferometry, if funded, will have provided essential information defining quantitative models of solar-surface magnetic



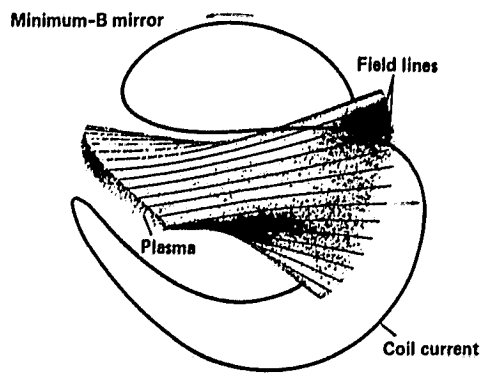


FIGURE 4.8 A magnetic-well mirror cell that has the property that the field strength increases in all directions from the geometric center.

cone by the cumulative effect of chance collisions with other trapped particles. This angle-dependent nature of the particle losses leads inevitably to trapped-particle distributions having empty loss cones, i.e., departing from the isotropic distribution in velocity angle that characterizes an ordinary gas, with the consequent negative implications for the stability of mirror-confined plasmas discussed below in the section on Current Frontiers of Research.

Mirror systems of the type described have confinement times that are low, bounded by the time required for an ion to be deflected through  $90^\circ$ . Such times would at best be marginal for a fusion reactor. However, mirror systems possess two major advantages for fusion purposes. First, a properly designed magnetic mirror field (with the field lines being convex toward the plasma surface) can form a deep magnetic well, a region in space surrounded by a magnetic field that increases outwardly in every direction (Figure 4.8). These magnetic wells have exceedingly high magnetic efficiency, having been shown to be capable of holding stable plasmas with pressures comparable to the energy density of the confining field (i.e., beta values approaching 100 percent). Second, because the confining fields are externally generated, mirror systems are inherently steady state.

Mirror fusion research, begun in the early 1950s, had by the mid-1970s reached a crucial turning point. A major triumph at that time was the control of high-frequency unstable fluctuations (called microinstabilities) to which the nonisotropic mirror plasmas can be subject. With this task accomplished, the rate of plasma loss slowed,

approaching the loss calculated to arise from the classical process of interparticle scattering. On the heels of this achievement came the demonstration of the generation and containment of high-beta plasmas at fusion temperatures. However, despite the encouragement from such an achievement, it was recognized that the single-cell mirror machine would have confinement too poor to satisfy the requirements for economic fusion power, i.e., too large a fraction of the fusion energy yield would have to be fed back to keep the system going. The challenge thus became to enhance the confinement in a mirror system to the point of engineering and economic practicality for a fusion power plant.

#### **Major Advances—the Tandem Mirror**

- A tandem-mirror system has mirror cells plugging the ends of a large-volume ignited plasma, resulting in a sharp improvement in overall confinement over the single-cell mirror.

In response to the challenge for improved mirror confinement, the tandem-mirror idea was conceived independently in the Soviet Union and the United States. In the tandem mirror, small-volume, relatively lossy, mirror cells plug the ends of a central mirror cell of large volume. The overall confinement of the open system is thus much improved, while preserving much of its high magnetic efficiency.

In this steady-state, linear fusion system, the fusion power is generated in a cylindrical chamber with solenoidal magnets (a linear assembly of simple circular magnet coils). The chamber is surrounded by a modularly constructed blanket for tritium breeding and neutron-energy recovery. At the ends, there are compact mirror end cells, followed by expansion chambers, where the field lines flare out. Within the expansion chambers are located special electrode arrays, forming a direct converter (resembling a Van de Graaff accelerator working backwards). These direct converters perform the dual function of spreading out the heat from the escaping plasma and of converting a large portion of the plasma's kinetic energy to direct-current electricity—power that can be recycled to maintain the plug plasmas.

The end-mirror cells serve two purposes: (i) to electrostatically plug the end losses from the central cell and (ii) to anchor the entire plasma against gross magnetohydrodynamic instabilities. In first-generation tandem-mirror devices, both of these purposes were served by shaping the end cells as magnetic wells and filling them with high-density plasma at high temperature, thereby creating a region of high positive

potential (as discussed in the following section), while at the same time providing a plasma "anchor" that stabilized the central plasma against gross motions. At this stage (circa 1977), the considerable progress achieved in mirror physics over the preceding decade was brought to bear in designing an entirely new type of confinement system from the ground up—one that actually performed very much as predicted.

In this first generation of tandem mirror experiments in the United States (TMX and Phaedrus) and Japan (Gamma 10), several key elements of tandem confinement were established:

- (i) The higher-density end cells electrostatically plugged the center cell in agreement with theory, giving a confinement parameter approaching  $10^{11}$  particles per cubic centimeter seconds;
- (ii) The higher-pressure end cells anchored the central cell gross motion for average beta values as high as 20 percent (in TMX); and
- (iii) The loss-cone-driven microinstabilities in the end cells behaved predictably and could be controlled in agreement with theory.

For economically motivated reasons, there have now been devised better ways of generating the required plugging potentials than the simple method used in the first tandem-mirror experiments. These methods, involving the use of thermal barriers, are described in the following section.

During recent years, the tandem-mirror program has benefited from a number of important theoretical advances, originating both in the United States and abroad. These include (i) theory of microinstabilities and their control; (ii) multiregion computer codes to calculate scattering and radio-frequency heating; (iii) computational codes for the magnetic fields generated by complex-shaped magnet coils; (iv) three-dimensional pressure equilibria and their gross stability in mirror fields; and (v) description of particle transport processes within the magnetic fields of tandem mirrors.

Turning to technological advances, mirror research has been responsible for some major contributions, including energetic neutral beams, high-field superconducting magnets of complex shape, and the development and application of microwave sources for plasma heating.

The United States has by far the largest program in tandem-mirror research, concentrated at the Lawrence Livermore National Laboratory, Livermore, California, with smaller programs at the Massachusetts Institute of Technology and the University of Wisconsin. Tandem-mirror research is also under way in Japan and in the Soviet Union.

### Current Frontiers of Research

- Building on previous successes, future progress toward fusion in mirror research will come from an increasingly quantitative understanding of the plasma processes that control the confinement of fusion plasmas in tandem-mirror systems.

The current frontiers of research in mirror confinement reflect the present need for a quantitative understanding of the physics of plasma confinement in magnetic fields. This need stems, of course, from the ultimate goal of fusion research—to achieve net fusion power by the most direct and economical means possible. Central to the issue of achieving a net fusion power yield from any magnetic-confinement system is an understanding of the rate at which heat is lost from the confinement zone. In mirror systems, these losses are of two kinds: (i) axial losses, i.e., losses through the mirrors and out the ends, and (ii) radial losses, i.e., losses by diffusion across the confining field lines. The physical mechanisms involved in these two kinds of losses are not the same, with the result that their study involves different physics issues.

In order to convey the nature of the issues that must yet be resolved, we will discuss them here in terms of four related conditions that must be met in order that confinement adequate for realizing a net positive fusion power balance can be achieved. These four conditions are as follows:

- Microstability, referring to the control of high-frequency oscillations, particularly as they might occur in, and interfere with the operation of, the end plugs;
- Axial confinement, pertaining to the need to achieve adequate control over any processes that lead to losses of particles that penetrate the electrostatic barriers created by the plug;
- Macrostability, referring to the maintenance of pressure equilibrium and stability of the confined plasma against gross unstable motion across the magnetic field; and
- Radial confinement, not the same as the previous condition, but rather referring to maintaining adequate control (through configuring the magnetic field and other means) over the rate of diffusion of the individual plasma particles across the confining field.

The early years of mirror research, and first-generation tandem-mirror experiments, provided both fundamental understanding and a data base from which to start the investigation of the physics under-

TABLE 4.3 Representative Tandem-Mirror Devices<sup>a,b</sup>

Device	Location	Period of Operation	Confinement Parameter (cm <sup>-3</sup> s) <sup>c</sup>	Thermal Barrier
MFTF-B	LLNL	1986-	(10 <sup>13</sup> )	Yes
TMX-U	LLNL	1982-	(10 <sup>12</sup> )	Yes
TARA	MIT	1984-	(10 <sup>11</sup> )	Yes
TMX	LLNL	1978-1981	10 <sup>11</sup>	No
Phaedrus	Wisconsin	1978-	10 <sup>10</sup>	No
Gamma-10	Japan	1983-	(10 <sup>12</sup> )	Yes
Ambal	USSR	1984-	(10 <sup>11</sup> )	No
Gamma-6	Japan	1978-1981	10 <sup>10</sup>	No

<sup>a</sup> Listed in descending device size, with U.S. devices listed first.

<sup>b</sup> Supporting single and multicell devices are STM at TRW, Constance at MIT, LAMEX at UCLA, and MMX at U.C. Berkeley.

<sup>c</sup> Projected parameters are in parentheses.

lying the above conditions. It is now, however, necessary to be much more precise in this understanding, in order to gain confidence that third-generation experiments will achieve their goals of closing the gap between where we are now and a close approach to net fusion power.

All the tandem-mirror devices operating or under construction are shown in Table 4.3. The values cited for the confinement parameter (product of plasma density and confinement time) are approximate and are given as indications of the performance level of the various devices.

In what follows, we will discuss briefly the physics issues involved in meeting the four conditions outlined above.

#### MICROSTABILITY

- Understanding of the properties of loss-cone-driven instabilities has led to their progressive suppression in a sequence of experimental steps and to their predicted elimination in a thermal-barrier tandem mirror.

As noted in the section on Major Advances—the Tandem Mirror, owing to their open-ended nature, mirror systems are vulnerable to high-frequency instabilities that can cause unacceptably high losses of particles through the mirrors. The degree to which a mirror cell is vulnerable depends on the degree of anisotropy of the species confined in the cell. In a tandem mirror, there is greater anisotropy in the end

plugs, where mirror action provides the dominant confinement force, than there is in the central cell, where electrostatic plugging predominates. It follows that concern for loss-cone-driven microinstabilities applies almost exclusively to the plug region.

The Livermore 2X-IIB experiment reduced the level and influence of microinstability by flowing warm ions through the hot, mirror-confined ion population. In TMX, the axial losses of ions from the central cell played the same function. This was described theoretically as a reduction of the destabilizing aspects of the mirror-confined ion energy distribution. A thermal-barrier plasma has this feature, without the need for additional flowing plasma. Validation of this theoretical picture will constitute a major step forward; early results from the new TMX-U experiment have been very favorable.

Theory and past experiments have identified the plasma conditions and parameters for microstability. Current and future experiments should be able to demonstrate quiescent plasma behavior in theoretically predicted stable conditions of higher temperatures and higher beta values, in this way delineating the constraints imposed on, and conditions required for, a mirror fusion power system.

#### AXIAL CONFINEMENT: CONTROL OF THE POTENTIAL PROFILE AND THERMAL BARRIERS

- Control of the axial potential profile is essential to tandem-mirror operation. The thermal-barrier end cell develops the plugging potential necessary for confining the central cell plasma with an end-cell density below that in the central cell, thereby reducing both the end-cell maintenance power and the required magnetic field.

The central cell of a tandem mirror is essentially a large-volume mirror confinement cell with a moderately large mirror ratio (strength of mirror field divided by the strength of the central field), with its ion loss channel plugged by a positive potential provided by the plugs. Power, incident in the form of neutral beams or microwaves, is required to generate the plugging potentials in the small-volume, lossy end cells. However, because of the large volume ratio between the central cell and the plugs, and because of the effectiveness of electrostatic plugging, the fusion power released from the central cell more than compensates for the power needed to maintain the plasmas in the plugs.

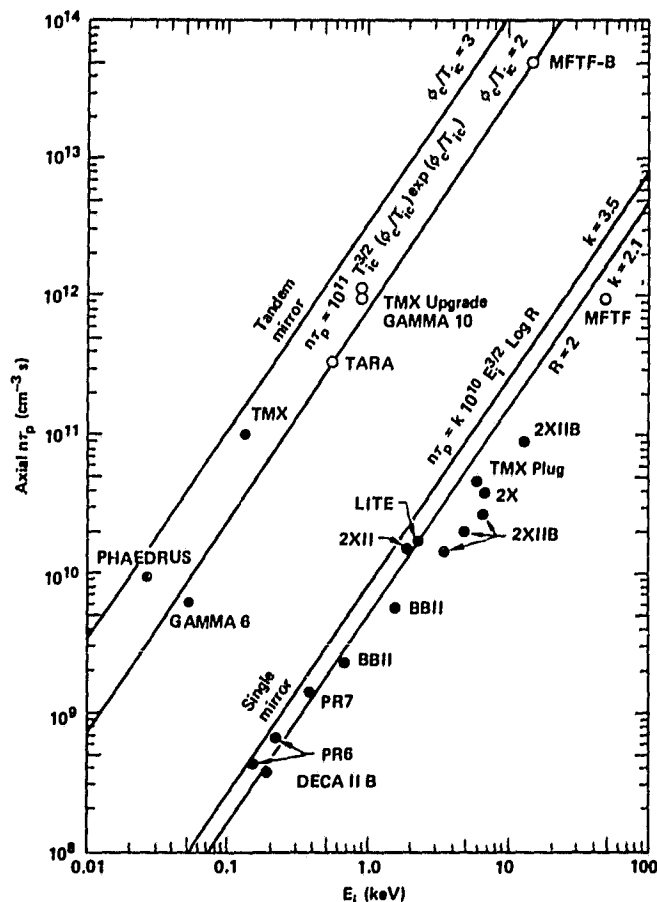


FIGURE 4.9 Variation of the confinement parameter  $n\tau$  with ion energy  $E_i$  for single-cell mirrors and the central cell of tandem mirrors, showing a strong improvement with increasing ion energy and a sharp increase due to electrostatic plugging. Here  $n$  is the plasma density,  $\tau$  the confinement time in the single cell or central cell,  $R$  the mirror ratio, and  $\phi_c$  the electrostatic plugging potential.

The contrast between the confinement ability of a tandem mirror and that of a single-cell mirror is illustrated in Figure 4.9, which plots the confinement parameter against ion temperature in kiloelectron volts. The points lying along the lower lines show experimental results from a variety of single-cell mirror experiments and their approach to the ideal theoretical values (set by classical collision-induced losses). Some departures are evident, usually the result of inadequate suppres-

sion of microinstabilities. The upper lines bracket the achieved and predicted confinement parameters for the central cell of various tandem-mirror devices. The dramatic improvement seen in the confinement parameter for a given energy over that achievable in a single-cell mirror results from the much greater effectiveness of electrostatic-plus-mirror confinement relative to mirror-only confinement. Theory predicts, and experiment confirms, that the electrostatic confinement depends exponentially on the ratio of the confining potential to ion temperature.

Achieving confinement in a tandem mirror implies an ability to control the profile of the electric potentials within the plasma in the vicinity of the plugs. The way such potentials are generated and controlled in the plug plasmas rests on the exploitation of a fundamental property of a plasma—its strong tendency to maintain charge neutrality. Even slight local departures from charge neutrality can create substantial electric potentials. This fact is put to practical use in the tandem mirror as a means of creating electrodeless, i.e., nonmaterial, potential-forming regions that control the containment of plasma particles.

The single-cell mirror naturally develops a positive potential in operation for a simple reason: the intrinsic mirror-only confinement time of hot ions is much longer than that of the rapidly scattering electrons. Charge imbalance leads to the buildup of a restraining potential (equal to several times the electron temperature), large enough to hold back the electrons, so that the rates of loss come into balance. In the simplest embodiment of the tandem mirror, that tested first in Gamma 6 and TMX, the confining potentials were generated by just this means: high-density mirror cells at each end generated the potentials (named ambipolar potentials) that electrostatically confined the ions of a lower-density central cell. In this way, a property of the plasma—its ambipolar potential—was used to enhance its own confinement.

While the original tandem mirror idea worked well to enhance mirror confinement times, from a future economic standpoint it had several drawbacks that prompted a search for improvements. The density of the plug plasmas had to be substantially larger than that of the central plasma, in order to establish the required potential "hill" confining the central cell ions. Furthermore, since the electron temperature controlled the magnitude of the total potential, in order to increase the potential it would have been necessary to heat *all* the electrons—plugs and central cell—to enhance the potential. Since the volume of the central-cell plasma is much larger than that of the plugs, this was



deemed to be an unnecessarily expensive and wasteful process. Finally, because the plugs had both high density and high ion energy, this pressure required prohibitively high magnetic fields.

It was reasoned that if the electrons in the plugs could be isolated from thermal contact with the central-cell electrons, a major economically related benefit would occur. The plug electrons could then be heated to a much higher temperature than the central-cell electrons (with a now much-reduced heating power input), and the potential would rise correspondingly. It was in fact predicted that the required confining potentials would be generated even if the central-cell plasma density exceeded that of the plug plasma.

The thermal barrier represents an improvement based on exploiting the possibility of controlling the relative charge-density profiles of electrons and ions in the end regions of a tandem mirror. It consists of a localized negative dip in potential between the central-cell plasma and the plugging potential. Such a potential dip serves to isolate the electrons trapped in the plugging potential from those in the central-cell plasma. It may be looked upon as a pair of back-to-back double layers of the type discussed in the physics of auroras. A comparison of typical potential/plasma-density profiles for conventional and thermal-barrier tandem-mirror systems is shown in Figure 4.10.

The thermal barrier represents a further manipulation of the axial potential beyond the idea embodied in the original tandem mirror. To maintain it, external power input is required in the form of electron heating and in the power required to pump out ions from the thermal-barrier region. Theoretical calculations show that, compared to the original tandem, the decrease in power required to maintain the plug plasmas (using neutral beams) more than compensates for the power required to form and maintain the thermal barrier. The decrease in permitted plug-plasma density also lowers the magnetic field required in the plugs, resulting in an important simplification in magnet design.

#### MACROSTABILITY: EQUILIBRIUM AND BETA LIMITS

- With careful attention to design of the end-cell magnetic fields, the open system's high-beta capability can be realized in a tandem mirror, with calculated beta limits in the range of 35-50 percent.

The requirement for a pressure equilibrium between the plasma and its confining field that is stable against gross plasma motion (magnetohydrodynamic instability) is common to all magnetic-confinement systems. The driving forces for such unstable motions are

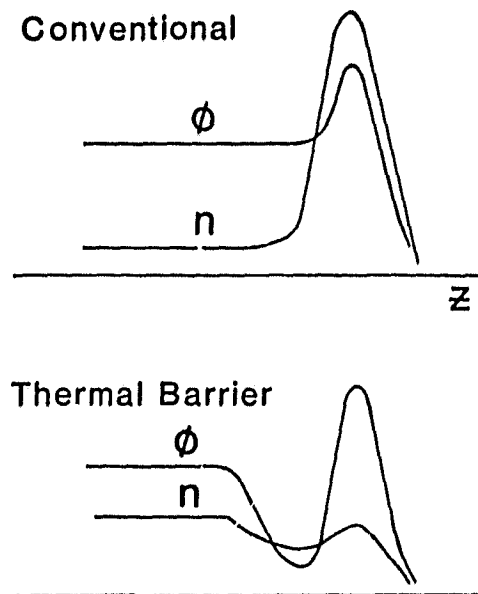


FIGURE 4.10 Axial profiles of tandem-mirror density  $n$  and potential  $\phi$  without (conventional) and with a thermal barrier, showing the sharply reduced end-cell density required when a thermal barrier is present.

the plasma pressure gradients themselves, abetted by effects associated with the curvature of the magnetic field lines and by centrifugal effects if the plasma is rotating. The field-line curvature enters in a fundamental way: regions where the field is convex toward the plasma are locally stabilizing; those concave are destabilizing. In a tandem mirror designed for gross stability, the good curvature regions are made to outweigh the bad, thereby achieving a favorable average.

The plasma is also subject to unstable perturbations that localize in regions of unfavorable curvature. Magnetically induced localizations, leading to ballooning instabilities, require line bending and consequently lead to beta limits. Electrostatic localization, leading to trapped-particle instabilities, requires a population of fast-bouncing particles that are trapped in the unfavorable-curvature region. Achieving stability sets a minimum for the fraction of particles that must visit both good and bad curvature regions. The challenge to magnet designers, blending together physics and engineering constraints, is to optimize the beta limits on stability and thereby optimize the magnetic efficiency. It appears that tandem-mirror systems can be designed that

exhibit average beta values that are substantial, of the order of 35-50 percent.

Many of the features of equilibrium and macroscopic stability theory have already been tested in previous mirror and tandem-mirror experiments. Features of the theory having to do with rotation effects associated with the radial electric fields in the central cell of a tandem-mirror system have yet to be tested. However, using the existing theory, conceptual tandem-mirror fusion power systems have been designed that are predicted to be stable to all such effects. If the underlying theoretical models are validated in upcoming experiments, an important physics aspect of the design of tandem-mirror fusion power plants will be secure.

#### RADIAL CONFINEMENT: PARTICLE TRANSPORT AND RADIAL POTENTIAL CONTROL

- Control of cross-field particle transport in tandem-mirror systems involves taking into account the symmetry of the magnetic fields and the effects of radial electric fields. Experiments are providing checks of the theory of these effects, which predicts that they can be made satisfactorily small.

In a tandem-mirror system, the end loss is plugged by an electrostatic potential. Since this potential cannot be maintained constant radially all the way to the plasma surface, it follows that the outer surfaces of the plasma are less well plugged than the inner regions. In such a system, the radial transport of particles then implies only that they are transported to regions where they are less well confined axially than they are in inner regions; they still end up by being lost through the ends rather than directly to the chamber wall (which need not be close to the plasma surface). This feature, a natural divertor action, can be a great practical advantage for fusion power generation.

Design of the magnetic-field configuration in tandem-mirror systems has a critically important bearing on the particle confinement in such systems. Typically, the end-mirror cells of a tandem mirror are designed with "quadrupolar magnetic well" type fields in order to ensure stability against gross (MHD) plasma instabilities. As a result of the essential azimuthal asymmetry of these fields, various complicated drift motions of the confined ions can occur that can cause these ions to diffuse radially across the confining field. This radial loss process is principally nonambipolar—ions escape across field lines, and electrons along field lines to the end walls. The problem of this so-called

"resonant transport," especially affecting the ions in nonaxisymmetric mirror fields, has been addressed theoretically, and scaling laws have been derived that can be used for comparison with experiment or for conceptual designs of tandem-mirror fusion power systems.

In recent tandem-mirror experiments, the rates of radial ion transport have been measured and have been found to agree within a factor of 2 or 3 with theory. In addition, by using special electrodes at the ends of the apparatus to control the radial distribution of electric potential (thus influencing the particle drift motions), marked improvements in radial confinement have been observed, in general agreement with expectations.

Currently, several approaches are under experimental and theoretical investigation for replacing the highly asymmetric quadrupolar end-mirror fields by alternative shapes that should permit totally, or nearly totally, axisymmetric central-cell fields. Based on present theory, these changes in geometry should reduce the asymmetry-related radial transport to negligible levels.

#### **Prospects for Future Advances in Mirror Confinement**

- In the growing quest for the most practical avenues to fusion power, the inherent flexibility of the mirror approach may lead to advantageous systems that are new or simpler.

One of the attractive features of mirror-based approaches to fusion power is the versatility and flexibility with respect to their design. The tandem-mirror idea is a prime example of these qualities, where the open-ended nature of tandem-mirror systems permits the manipulation and control of both the magnetic and the electrostatic aspects of its operation in a variety of ways. First steps in the evolution of the tandem-mirror idea are already being taken with the introduction of the thermal barrier idea, aimed at more effective control of the confining potentials with expected future economic gains. A coming challenge for tandem-mirror researchers will be to find ways to accomplish this and other objectives in simpler ways.

Simplification, with its resulting engineering and economic advantages, may be sought in improved magnetic configurations and in simpler means of potential generation and control.

With respect to the tandem-mirror magnetic configuration, there is hope, based on low-temperature results, that axially symmetric (or nearly so) versions of the tandem could be designed that would preserve the high-beta qualities of the present nonaxisymmetric con-

figurations, while at the same time suffering less particle transport and being much simpler and cheaper to construct.

With respect to simplified means of potential control, there exists the theoretical possibility that designs or operating modes for the tandem-mirror plugs can be found that retain the advantages of present thermal barrier ideas but achieve the equivalent result by much simpler means. One example would be the negative tandem mirror, operated at a net negative potential, with magnetically confined electrons plugging the ion leak channel.

The above are intended to illustrate some of the possibilities that may arise when two fundamental ideas—the magnetic-mirror effect and the control of plasma by self-generated electrostatic potentials—come together as they do in the tandem mirror. Increased understanding of basic mirror principles should advance the mirror approach to magnetic confinement. The goal is a simple and effective fusion reactor. As the most prominent mirror-based approach, the tandem-mirror concept has been built on a series of innovative ideas, which have been verified in the first generation of experimental devices. The momentum created by these successes should carry us near a demonstration of fusion breakeven by the end of this decade.

## ELMO BUMPY TORUS

### Introduction

- The Elmo Bumpy Torus (EBT) concept relies on superhot mirror-confined high-beta electron rings to stabilize a core plasma in a mechanically simple, steady-state toroidal configuration.

Plasmas confined in toroidal or mirror magnetic geometries tend to be unstable in regions where the magnetic field lines bulge away from the plasma, i.e., regions of "bad curvature." A generic method for improving stability is to create a superhot component in the bad-curvature region. The diamagnetic current from a sufficient number of these hot particles produces a local minimum, or well, in the magnetic field (a minimum-B field). If the motion of the superhot component is dynamically decoupled from the remaining plasma, the minimum-B field will produce a stable confinement configuration. This principle is the basis of the EBT.

The basic building block of an EBT is the single canted mirror sector shown in Figure 4.11. The mirror sectors (typically 24) are connected toroidally, forming a highly accessible and simple mechanical structure

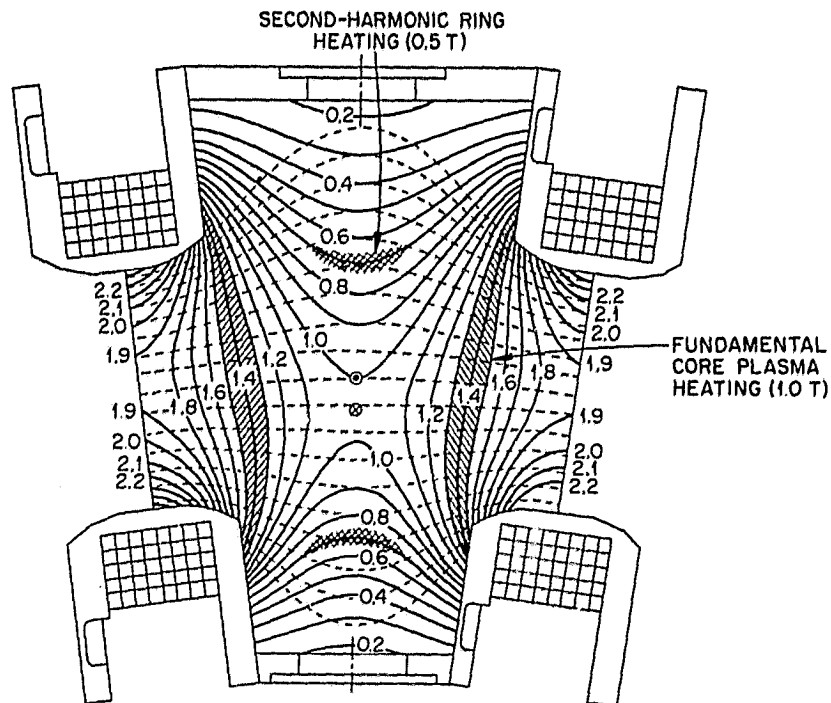


FIGURE 4.11 A single canted mirror sector of a bumpy torus, showing field lines (dashed lines), contours of constant field strength (solid lines), and electron cyclotron resonance zones (hatched).

that is operated steady state. The coil spacing causes the magnetic field lines to bulge out between magnets, creating a bumpy magnetic field and providing an absolute trap for charged particles. Stability of the equilibrium is provided by very hot, stable electron-ring plasmas (ring temperatures of 100-500 keV) generated by steady-state microwave power. The hot electron-ring plasmas are created in the annular region where the applied microwave frequency equals the second harmonic of the local electron cyclotron frequency. The stored energy density in the rings is found to be comparable with the local magnetic field energy density; hence, the ring-plasma beta can be high, up to 50 percent in some cases. These rings can be formed in the regions where the toroidal core plasma would otherwise be susceptible to the interchange instability.

The essence of the EBT concept is the generation of a toroidal series of hot electron rings for the creation, stabilization, and buildup of the

fusion-relevant toroidal core plasma that threads through them. The objective of the EBT program is to demonstrate the viability of this concept, ultimately for a reactor. Key objectives are to demonstrate stable confinement of ring and core plasma and efficient microwave heating of ring electrons.

EBT research in the United States is centered at the Oak Ridge National Laboratory, with smaller efforts at McDonnell Douglas, TRW, JAYCOR, SAI, and various universities. There is also a major program in Japan.

### Major Advances

- In EBT experiments, the production and maintenance of superhot electron rings by microwave heating using 28-60 GHz gyrotrons obeys theoretical predictions and scales favorably to a reactor. The stability of the ring depends on dynamic decoupling from the core plasma, and sets a limit on the core-plasma beta, which has not yet been tested experimentally.

Experiments in the Elmo linear mirror, and thereafter in the EBT-1 toroidal device, established that stable hot electron ring plasmas could be generated steady state and that the rings could stabilize a warm, moderately dense core plasma (plasma density of  $10^{12}$  particles per cubic centimeter and electron temperatures of 100-400 eV). The primary limit on particle and energy density was the applied frequency and the available electron cyclotron resonance heating (ECRH) power. The success of EBT-1 with 10.6- and 18-GHz heating prompted the development of higher-frequency, higher-power, steady-state microwave sources.

In 1978, the first EBT scaling experiments at higher magnetic field and microwave frequency were performed with a 28-GHz gyrotron at about 30 kW steady state. The power levels increased steadily, with routine plasma operation at 200 kW steady state achieved in 1981. Most recently, a prototype 60-GHz gyrotron was tested at 200 kW steady state.

EBT experiments have shown that production of hot electrons by electron cyclotron heating is an efficient process. Data from EBT and other single-frequency ECH hot-electron experiments have indicated that the ring temperature obeys a simple scaling law, in which the hot-electron radius of gyration (which is proportional to the square root of its temperature) is limited to 5-6 percent of the magnetic-field curvature scale length. In addition, heating at several frequencies close

in value was shown to improve the heating efficiency (by increasing the density) an order of magnitude on the Symmetric Tandem Mirror (STM) experiment, a linear multicell mirror device with EBT-type hot-electron rings.

Experimentally, ring losses appear to be classical, primarily determined by collisional slowing down and scattering on the core plasma at low energies and by synchrotron radiation at high energies. Since the rings in an EBT reactor occupy only a small fraction of the plasma volume and their thickness is larger than the hot-electron gyroradius, the ring power loss would be fairly modest for 1-2 MeV electrons.

The stabilization by the rings depends critically on whether the rings are rigid, i.e., dynamically decoupled from the behavior of the core plasma. Experimentally, ring decoupling is clearly achieved in certain regimes of operation. Because the usual theory of ideal fluids cannot explain this phenomenon, a new type of quasi-kinetic stability theory has recently been developed for instabilities in EBT caused by unfavorable curvature. This theory yields stability for certain parameter values, not inconsistent with experimental operation. However, it also predicts that, at a relatively low core-plasma pressure, coupling between ring and core plasma will occur and generate an unstable configuration. This beta limit cannot be tested on the present generation of EBT devices.

#### Current Frontiers of Research

- The emphasis in current EBT research is on increasing the core plasma density and temperature, so as to test the beta limit, and on understanding and optimizing the confinement of the core plasma.

Although EBT has made substantial progress in containing core plasma, to date the density is limited to a few times  $10^{12}$  particles per cubic centimeter, or about 10 percent of the ECRH cutoff density limit. There is a high priority to show that higher densities can be achieved. One possible technique would be to use wave energy from the high-field region, as opposed to the conventional low-field launch, and to control the polarization of the wave. Another technique is slow-wave ion cyclotron resonance heating (ICRH), which has been effective in raising the plasma density in the Japanese Nagoya Bumpy Torus experiment (NBT).

Ion cyclotron heating is being developed to heat the core plasma ions and to explore confinement of hot ions in EBT. Fast-wave ion heating is available on present experiments at power levels comparable with,



or greater than, that absorbed by the electrons. If the density can be raised, the applied ICRH power should heat the ions more efficiently.

With higher density and hotter ions, it may become possible to check the plasma beta stability limit predicted by theory. The beta limit is important in determining the operating regime for future experiments and in assessing reactor feasibility. For instance, there is a trade-off between plasma-beta and ring-power economics, in that high beta would require thick rings, whereas thin rings are desirable for minimizing their energy investment.

Even with ideal operation of the rings, the EBT configuration must be able to contain a core plasma long enough against the diffusive effects of particle collisions. An EBT system, taken to be dominated by classical collisions, would be marginally adequate for ignition in a modest 1000-MW reactor. However, there is concern that anomalous transport due to drift wave fluctuations may degrade confinement.

#### **Prospects for Future Advances**

- The next stage of the EBT program could involve a scaled-up experiment with improved confinement. Alternative configurations are under investigation, and aspects of the EBT concept have application also to advanced tokamaks and mirrors.

The next evolutionary stage of the EBT program would be to test confinement in larger standard bumpy tori at parameter regimes of higher density (in the range of  $5 \times 10^{13}$  particles per cubic centimeter range) and higher temperature (above 1 keV) for the toroidal core plasma.

From theory have come a number of ideas for improved containment of particle orbits, such as advanced coil designs, reversing the ambipolar potential, reconfiguring the standard bumpy torus into bumpy straight sections with high-field corners, and hybrid combinations of an EBT with rotational transform. Recent theoretical work also suggests that the stability of tokamaks, stellarators, and mirrors can be enhanced by the introduction of energetic particles similar to those in EBT.

In addition, EBT research has had other benefits. The desire to provide higher-frequency, more-powerful ECRH sources for EBT has resulted in a national program for microwave-source development. These gyrotrons are being used extensively in the tokamak program for local heating and assisted start-up and in the tandem-mirror program for thermal-barrier production.

## REVERSED-FIELD PINCH

### Introduction

- The reversed-field pinch is, like the tokamak, a toroidal confinement system. Its distinguishing features include high beta and the potential for a compact reactor in which the plasma currents themselves provide heating to ignition.

The reversed-field pinch (RFP) is a close cousin of the tokamak confinement system. Like the tokamak, it is a toroidal device that combines a toroidal magnetic field with a poloidal magnetic field to confine a plasma. Figure 4.12 shows the direction that the magnetic fields point in different parts of the RFP plasma. It is the reversal in the direction of the toroidal field near the wall that gives the reversed-field pinch its name. An important difference between the RFP and the

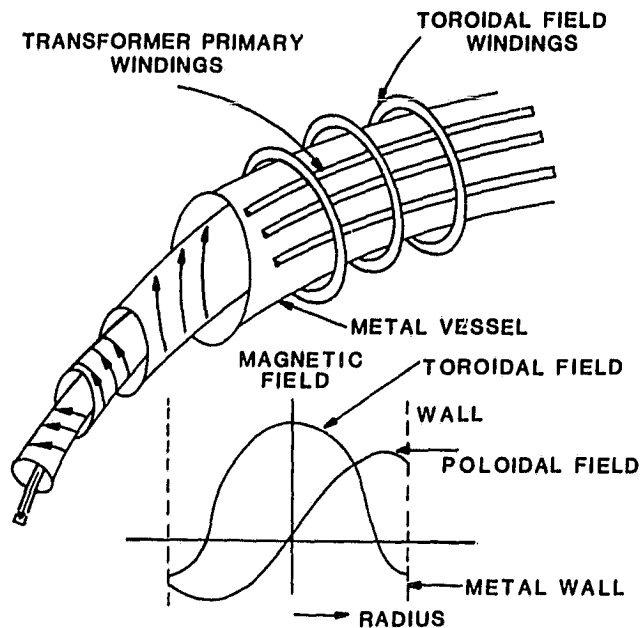


FIGURE 4.12 Magnetic fields in the reversed-field pinch. The plasma current is induced by the transformer primary windings, whereas the toroidal magnetic field is produced initially by the toroidal field windings. The direction of the magnetic field lines on surfaces at different radii is also shown. Notice that the pitch of the field-line helices reverses near the walls, because the toroidal magnetic field changes sign. Hence the name reversed-field pinch.

TABLE 4.4 Representative Reversed-Field Pinches

Device	Location	Major Radius (m)	Minor Radius (cm)	Plasma Current (MA)
OHTE <sup>a</sup>	GA	1.24	19	0.25-0.50
ZT-40	LANL	1.14	20	0.06-0.24
ETA BETA-2	Italy	0.65	12.5	0.05-0.20
HBTX 1-A	UK	0.80	26	0.10-0.50
TPE-IR(M)	Japan	0.50	9	0.13
REPUTE <sup>b</sup>	Japan	0.80	20	(0.4)
STP-3M <sup>b</sup>	Japan	0.50	9	(0.3)

<sup>a</sup> Privately funded.<sup>b</sup> Under construction 1984.

tokamak is that in a tokamak the dominant confining field is the toroidal field, produced by an external magnet winding, whereas in an RFP it is the poloidal field produced by the plasma current that is responsible for plasma confinement. To maintain stability in a tokamak, the poloidal field, and hence the plasma current, must be kept small compared with the toroidal confining field. In an RFP, the toroidal and poloidal magnetic fields are of comparable magnitude, so for a given toroidal magnetic field much higher plasma currents are carried in an RFP.

These differences can be exploited in a reactor. The high plasma currents allowed in an RFP are expected to be sufficient to heat the plasma to ignition without the need for auxiliary neutral-beam or radio-frequency heating systems. An important quantity in fusion reactor design is the engineering beta, which is defined as the ratio of the plasma pressure to the pressure exerted by the magnetic field on the magnet windings. This quantity can be rather large in an RFP because the toroidal field at the windings is small, and the poloidal field strength is much smaller at the magnet windings than at the plasma surface. The engineering beta in present RFP experiments is typically 10 percent. With this value of engineering beta, the magnet windings in a reactor could be made of copper rather than superconductors. These features have led to the design of compact RFP reactors that offer several potential advantages over the larger conventional reactor designs.

Present RFP experiments (see Table 4.4) operate with a plasma current only 1-2 percent of that needed in a reactor. The major research goals of the RFP program therefore are to raise the plasma current and (i) maintain the high beta currently achieved, (ii) demonstrate adequate

confinement and plasma heating, and (iii) develop the necessary technology for exploiting the high-power density potential of the RFP reactor.

RFP research in the United States is centered at the Los Alamos National Laboratory. Both Europe and Japan are also active in RFP research.

### Major Advances

- We now understand that the RFP is a minimum-energy state. This helps to explain its stability and persistence and may permit steady-state operation of an RFP reactor.

The last decade has seen considerable progress in RFP research both in the United States and abroad. The most important advance has been the understanding that the RFP is one of a class of minimum-energy states. All such minimum-energy states lie on the curve shown in Figure 4.13, which shows the ratio of the toroidal magnetic field at the wall to the average toroidal magnetic field ( $F$ ) versus the ratio of the poloidal field at the wall to the average toroidal field (called  $\theta$ ). As  $\theta$  is increased (by increasing the plasma current, for instance)  $F$  must decrease, and when  $\theta$  reaches 1.2, the toroidal field at the wall must vanish. (This configuration, called a spheromak, is discussed in the section on Compact Toroids.) When  $\theta$  exceeds 1.2, the toroidal magnetic field at the wall must become negative, and we have an RFP.

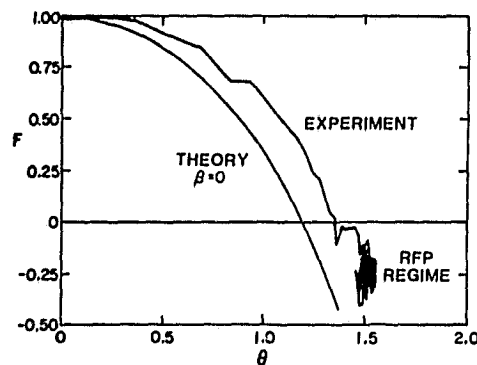


FIGURE 4.13 The  $F$ - $\theta$  diagram.  $F$  is the ratio of the toroidal magnetic field at the wall to the average toroidal magnetic field, and  $\theta$  is the ratio of the poloidal magnetic field at the wall to the average toroidal field. The plot shows how  $F$  depends on  $\theta$  for the minimum-energy state.

The fact that the RFP is a minimum energy state explains much about the stability and persistence of this configuration and leads to the possibility of steady-state, or continuous, operation of an RFP reactor.

Early RFP experiments were plagued by very-high-energy losses caused by impurities in the plasma. These losses were so serious that temperatures did not exceed 50 eV. Improvements in vacuum systems and vacuum wall materials now reduce impurities to the point where the energy losses attributable to impurities are only 5-20 percent of the total energy losses. Present experiments typically reach temperatures of 200 eV, with electron densities of  $(1-4) \times 10^{13}$  particles per cubic centimeter, using a magnetic field at the coils of about 1 kG; one smaller experiment has produced 600-eV plasmas.

Another major step forward has been the confirmation that RFP configurations can be formed over comparatively long times. Until the induced plasma current becomes large enough to cause the pitch of the helical magnetic field lines near the wall to reverse, the plasma is potentially unstable. For this reason, early experiments formed RFP plasmas so quickly that instabilities did not have time to develop. Recent experiments have shown that such fast formation schemes are not required. The slower formation schemes allow lower-voltage operation and simplify engineering problems.

#### **Current Frontiers of Research**

- The key issue in RFP research is whether its confinement will be adequate when operated at high plasma current.

Five RFP devices, of which two are in the United States, are currently operating (see Table 4.4).

Confinement properties of the RFP at higher plasma currents are the subject of continuing investigation. The energy confinement time must be increased to 1000 times its present value of 0.25 ms to meet reactor requirements. The temperature and density must also be increased by large factors, while beta must be maintained at its present value. It is important to ascertain as soon as possible whether the RFP concept will scale to the desired levels of confinement, by understanding the internal processes that determine the rate of energy leakage from the plasma across the magnetic field lines as well as the processes that sustain the RFP configuration. Theorists are beginning to use sophisticated three-dimensional magnetohydrodynamic (MHD) computer codes to study the internal operation of the RFP, and experimentalists

have detected MHD modes similar to those predicted by the theoretical codes.

Four other areas of current research are described below:

- (i) The principal barrier to raising the plasma current is the resulting damage to the very thin metal vacuum walls used in present equipment. This wall damage should be reduced by use of equilibrium control and limiters. Electronics circuits are used to control the equilibrium position of the plasma, and preliminary results include longer plasma lifetimes and reduced plasma interactions with the wall. Several limiter designs, which protect the thin wall by limiting plasma size, are being tested.
- (ii) The sensitivity of RFPs to errors in the magnetic fields is being investigated. Reductions of the field errors in existing devices (caused by perturbations such as pump ports, nearby iron, and insulating gaps in the conducting shell) have dramatically increased the plasma lifetime, and designs of future machines call for much lower field errors than those in the present generation machines.
- (iii) Improved formation schemes are being investigated including the ramped formation, which begins with a low-current RFP and then gradually increases the plasma current and density to the desired levels. This procedure avoids having to produce full plasma current before the stable RFP configuration is established.
- (iv) The transformer technique now used in RFPs can only sustain a plasma current for a limited time. Several techniques for steady-state current drive being tested for use in tokamaks might be applicable to an RFP, but another technique, which is unique to the RFP concept, is currently being studied most intensively. This technique is to oscillate the currents in the magnet windings at audio ( $\sim 2$  kHz) frequencies. Theory predicts that the plasma will rectify the oscillations and maintain a net toroidal plasma current. Recent experiments have confirmed some of the assumptions made in the theory, and more elaborate experiments are being planned.

#### **Prospects for Future Advances**

- Larger reversed-field pinches have been proposed in several countries, aimed at reactorlike plasma densities and temperatures.

Results from the present RFP experiments appear sufficiently promising that larger RFP devices are being proposed in the United States, Europe, and Japan. These machines would be at least twice as large as present experiments and carry over four times more plasma current. With these machines, temperatures in the kiloelectron-volt range should be attained, with an electron density of approximately  $10^{14}$  particles per cubic centimeter and an energy confinement time in the 10-ms range.

## COMPACT TOROIDS

### Introduction

- Compact toroids are a class of toroidal plasma configurations that might lead to a smaller, less expensive reactor core. Substantial progress in understanding the confinement properties of the various classes of compact toroids is needed to evaluate their potential reactor advantages.

Compact toroids (CTs) are a class of toroidal confinement configurations that do not require any magnet coils or vacuum chamber to link the plasma through the hole in the doughnut-shaped configuration. A magnetic surface called the separatrix divides the open field lines on the outside from the closed field-line or flux-surface structure of the CT on the inside. All the fields inside the separatrix are supported by currents inside the plasma; the only fields that are supported by magnet coils are the solenoidlike fields outside the separatrix.

Although a broad class of confinement schemes is possible within the CT area, the spheromak and the field-reversed configuration (FRC) are being studied most intensively at present. In their fundamental form, both are axisymmetric, like the tokamak and reversed-field-pinch. However, nonaxisymmetric variations can be added to CTs and, in fact, have been successfully used to help stabilize the FRC.

The fundamental difference between these two types of CTs is that, inside the separatrix, the spheromak has both poloidal and toroidal field components (see Figure 4.14) like the tokamak and the reversed-field-pinch, but the FRC contains no toroidal field, only closed poloidal field lines. This deceptively simple change yields completely different equilibrium, stability, and confinement properties.

Although CTs are at a comparatively early stage of development, gross stability and high betas have been confirmed at temperatures of about 100 eV. If the energy confinement improves favorably at higher

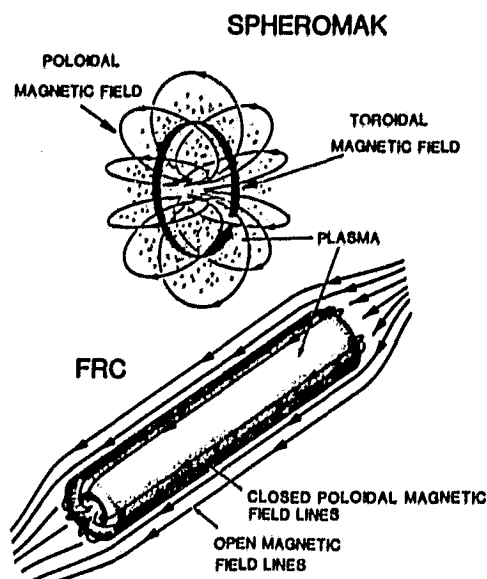


FIGURE 4.14 Schematic representations of a spheromak and a field-reversed configuration (FRC). Note the closed magnetic-field region where the plasma is confined. The FRC has an elongated prolate shape, whereas stable spheromaks are oblate.

values of temperature and magnetic field, while preserving the high beta and stability, CTs will offer important advantages for the fusion power core of a reactor. The large beta would allow a high power-density plasma to be supported by modest fields at the magnet coils. If the technology of the first wall (nearest the plasma) can be developed to accept the high power, then much smaller and less expensive reactor cores could be built. The simple geometry of the magnet coils and vacuum chamber allowed by the CT configuration adds to these advantages.

Although the terms compact toroid, spheromak, and field-reversed configuration have all been coined during the past decade, the concepts are all more than 20 years old. Both spheromaks and FRCs had been produced in the laboratory by 1961. Some characteristic parameters of present spheromak and FRC experiments are given in Table 4.5.

The particle ring was another type of CT also conceived in the 1950s. The particle ring differs from other CTs in that the fields inside the separatrix are supported by currents carried by high-energy particles (electrons or ions) whose gyration radii are comparable with the major



radius of the torus, hence the name particle ring. Complete field reversal (CT formation) was achieved with electron rings in 1972, but reactor studies have indicated that neither electron nor ion particle rings are likely to produce economically attractive reactors. However, some work on particle rings continues, because a merger of such rings with spheromaks or FRCs has the potential of aiding stability, heating, and sustainment of CTs.

Compact toroid research in the United States is conducted at Los Alamos, Princeton, the University of Maryland, Spectra Technology (formerly Mathematical Sciences Northwest), and several smaller institutions. Japan and the Soviet Union are also particularly active in this area.

TABLE 4.5 Representative Compact Toroids

Device	Location	Major Radius (m)	Minor Radius (cm)	Toroidal Plasma Current (MA)	Program Contributions <sup>a</sup>
<i>Spheromaks</i>					
CTX	LANL	0.25	15	0.4	C,F,S,ST
COP	U. of Wash.	0.04	4	0.01	F,M
PS-2	Maryland	0.09	9	0.10	C,F
Proto S-IC	PPPL	0.12	8	0.06	C,F,S
S-1	PPPL	0.50	27	0.2 (0.4)	C,F,S
CTCC-1	Japan	0.26	14	0.2	C,F,M
<i>Field-Reversed Configurations</i>					
FRX-C	LANL	0.07	3	1.5	C,S,T
CTTX-1	Penn State	0.02	1	0.14	H,T
TRX-1	Spectra	0.045	2	0.75	C,F,S
TRX-2	Spectra	(0.045)	(2)	(0.75)	(C,F)
BN-1	USSR	0.05	2.5	0.5	F,T
TOR	USSR	0.07	3	1.1	F,T
TL	USSR	0.04	2	0.3	F,T,CH
NUCTE-2	Japan	0.028	12	1.6	C,F
OCT	Japan	0.035	2	0.5	F,T
PIACE	Japan	0.026	1	0.6	C,S,T
STP-L	Japan	0.01	1	1.2	C,S

<sup>a</sup> Program contribution codes are as follows: confinement (C), compressional heating (CH), formation (F), merging (M), stability (S), sustainment (ST), translation (T).

### Major Advances

- Substantial experimental and theoretical progress in the last decade has reawakened interest in compact toroids.

Substantial progress has been made during the past decade in both forming and understanding spheromaks and FRCs. Although important theoretical and experimental work was accomplished earlier, the results were not sufficiently convincing to capture the attention of a major segment of the fusion community. Important advances in plasma theory and computation, and some pioneering experimental work, motivated a closer examination of CTs. Improvements in diagnostics, impurity control, and other experimental techniques developed in the fusion community have also contributed strongly to the recent successes. One measure of the rapid progress that has been made is shown by the improvement in plasma lifetime plotted in Figure 4.15.

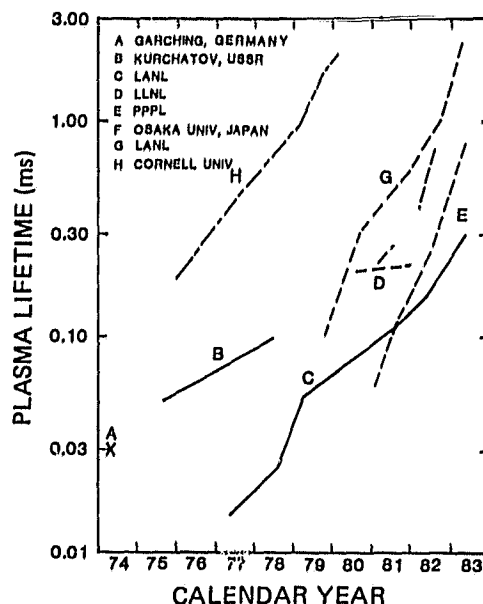


FIGURE 4.15 The maximum compact-toroid lifetimes produced by a variety of experiments during the past 10 years. The solid lines are FRCs, and the dashed lines are spheromaks.

## SPHEROMAKS

- Spheromaks are compact toroids with both poloidal and toroidal magnetic-field components; significant progress has been made in impurity control, in formation and sustainment techniques, and in extending the lifetime of the plasma.

The long lifetimes recently achieved (see Figure 4.15) are evidence that spheromaks can be maintained in stable configurations for many (hundreds of) dynamic time scales. These positive results are dependent on maintaining the proper plasma shape and boundary conditions, as prescribed by stability calculations. In addition, spheromaks have been produced with temperatures over 100 eV, indicating that they are no longer dominated by light-ion impurity radiation. This was first achieved in 1983 on the CTX device at Los Alamos, using a source with electrodes. Typical spheromak plasma parameters are shown in Table 4.6, along with parameters for FRCs.

Major breakthroughs have also been made in the techniques of forming and sustaining spheromaks. The older techniques formed the plasma on the dynamic time scale, i.e., the time scale determined by the "springiness" of the magnetic field and the mass or inertia of the plasma. This rapid formation required high-voltage electrical technology that would be unattractive for projected reactors. The Proto S-1A device at Princeton, guided by sophisticated computations, was the first to demonstrate a slower technique that would operate close to the resistive time scale. Reactors based on this slower technique could use standard rotating machinery to power the spheromak source.

The breakthrough in sustainment was achieved on the CTX device when magnetic fields and plasma density were held constant for 1 ms, a time long compared with the natural decay time of the configuration, by applying continuous electrical currents from the electrodes of the plasma source. The technique is based on a minimum-energy principle, which the spheromak shares with its cousin the reversed-field pinch, namely, that the plasma and magnetic fields within a conducting boundary relax to a state of minimum energy under the constraint of conserved magnetic helicity (linked fluxes). On a longer time scale, the configuration would decay as the currents are decreased by the plasma resistivity. In the sustainment process, the source supplies a continuous flow of a helicity into the separatrix region of the spheromak to replace that dissipated internally by the resistive losses, and the spheromak redistributes the fields as it continues to relax toward its minimum energy state. The sustainment experiments in CTX indicate

TABLE 4.6 Typical Parameters for Compact Toroids

Compact Toroid	Lifetime (ms)	Energy Confinement Time (ms)	Density ( $10^{14} \text{ cm}^{-3}$ )	Electron, Ion Temp. (eV)	Magnetic-Field Strength (kG)	Plasma Beta (%)	Major Radius (cm)	Minor Radius (cm)
Spheromak	1.1	0.06	0.6	100	2.0	10	25	15
Field-Reversed Configuration	0.3	0.08	50	100	6.5	90	7	3

that it may be possible to create and then sustain spheromaks continuously using dc power, obviating any need for current drive and perhaps also for additional heating.

#### FIELD-REVERSED CONFIGURATIONS

- Field-reversed configurations are compact toroids having poloidal magnetic field only; major advances have been made in understanding confinement scaling and equilibrium physics, in achieving increased confinement parameters, and in stabilizing the rotational instability using quadrupole magnetic fields.

The increased effort in FRC studies in the United States initiated 7 years ago was largely motivated by experimental results from the Soviet Union and Germany during the early 1970s. Figure 4.15 shows that significant progress has been made since that time in extending the lifetime of FRCs. In part, the increased lifetimes have been achieved by using theoretical models of transport and equilibrium to guide the experiments. The confinement scaling predicted by these models has been confirmed by experiments. The best FRC confinement parameters have been produced on FRX-C, which has achieved values of the confinement parameter of about  $4 \times 10^{11}$  particles per cubic centimeter seconds. Plasma parameters consistent with this value are given in Table 4.6.

The latest jump in the FRC lifetime (see Figure 4.15) was achieved on FRX-C by stabilizing the rotational mode by a technique first developed on the PIACE experiment in Japan in 1982. The stabilization technique uses special (quadrupole) fields to produce small nonaxisymmetric bumps on the FRC.

#### Current Frontiers of Research

- The physics of particle and energy transport in spheromaks is largely unknown and is a central issue for assessing the promise of this configuration; other areas of research include stability, heating, and sustainment. Particle and energy transport are better understood for FRCs than for spheromaks, but unresolved questions remain. Although existing FRCs are stable, it is unknown whether this will remain the case for reactor-sized plasmas; translation experiments may lead to improved FRCs, but formation of the configuration on a slow time scale remains an important problem.

The most important issue for spheromaks is to understand the particle and energy transport processes. In the higher-temperature plasmas ( $\sim 100$  eV), the energy loss appears to be dominated by particle transport. Since the beta value is higher than stability theory would predict, the plasma pressure may be driving turbulence that results in particle loss. In addition, edge conditions near the separatrix appear to affect strongly the plasma behavior, particularly at higher temperatures. These complex physics issues can be translated into a practical concern. If the boundaries are made properly, will the energy confinement time increase sufficiently with size and field to meet the requirements of a practical reactor? Much of the near-term research will be focused on this question.

Other important areas of research include the sustainment and heating of spheromaks. The dc current technique for sustainment will be examined to determine the efficiency of helicity injection, as well as its effects on energy confinement. Studies of radio-frequency heating are planned, as well as other auxiliary heating techniques such as compression and particle beams.

Transport physics is also a major issue in FRC research but is somewhat more developed than for spheromaks. Particle transport models are consistent with experiments, but two related issues remain unresolved, namely, additional energy-loss processes and stability. In the largest experiment (FRX-C), the particle transport accounts for slightly less than half of the energy loss. Oxygen and carbon radiation are not significant, but radiation from heavier impurities and thermal conduction may be important energy-loss mechanisms. Understanding and reducing the energy loss by radiation and conduction will become even more important as scaling experiments continue to reduce the particle loss.

The instability issue may arise when FRCs are scaled to larger size to improve confinement. In spite of substantial theoretical progress, existing theories cannot predict whether FRCs large enough to provide reactor-level confinement will be stable or unstable. Continued theoretical and experimental efforts are being directed to help resolve this issue.

Translation of the FRC out of the source into a steady-state solenoidal field region is an integral part of some FRC reactor concepts. Translation has been successfully demonstrated in Soviet, Japanese, and U.S. experiments. It is currently being studied in the United States as a means to facilitate longer plasma lifetimes, diagnostic access, impurity control, and alteration of the FRC's radial profile, which affects the particle loss rate.

Formation of FRCs on a slow time scale is important for the same reasons as for spheromaks. Several proposed concepts are being studied theoretically and await experimental verification.

#### Prospects for Future Advances

- At the current rate of progress, in the next 10 years or so the unique features of compact toroids should be well enough understood to assess their potential in comparison with other advanced concepts.

During the next 10 years, substantial progress is expected in understanding the transport processes for both FRCs and spheromaks. For spheromaks, the PS-2 device at the University of Maryland and its successor (e.g., the proposed MS experiment) will study mixed formation (i.e., a combination of inductive and electrode drive) and the transport of higher-density (about  $10^{15}$  particles per cubic centimeter) plasmas. The S-1 experiment at Princeton and its upgrades will address inductive formation, transport, gross stability, and auxiliary heating. The CTX experiment at Los Alamos and its upgrades will investigate the transport, and also the sustainment by currents from external electrodes, of spheromaks with densities in the range  $10^{13}$ - $10^{14}$  particles per cubic centimeter. If these are successful, the confinement parameter for spheromaks should exceed  $10^{11}$  particles per cubic centimeter seconds.

Similarly, the FRX-C and TRX-2 experiments at Los Alamos and at Spectra Technology (formerly Mathematical Sciences Northwest), respectively, will be extended for further confinement scaling studies on FRCs. The next generation experiments, however, will probably require the development of slower formation techniques. The Soviet FRC experiments are expected to continue to investigate formation issues and compressional heating, probably using imploding liners. The Japanese FRC experiments will probably continue to address translation, transport, and energy-balance questions.

In addition, plasma engineering tests are needed to verify the feasibility of the CT configuration to meet requirements imposed by reactor considerations. These tests should include slow formation techniques for both spheromaks and FRCs and, where appropriate, auxiliary heating, sustainment, and feedback control. In addition, small experiments on merging particle rings with CTs should have been completed, to see if particle rings offer substantial advantages for CTs for stability, heating, or sustainment. One possible experiment would

be ion-beam injection into the S-1 spheromak, to test for plasma heating and stabilizing effects against the gross tilt/shift mode.

## PLASMA HEATING

### Introduction

- To heat a fusion plasma to ignition, about 30-50 MW of power will be needed—either in the form of beams of very energetic neutral particles or, preferably, in the form of radio-frequency power.

In order to generate a significant level of power output from the D-T fusion reaction, it is necessary to attain thermonuclear plasma temperatures (see Figure 4.2). In a typical reactor-grade plasma, it will be necessary to provide 30-50 MW of power for several seconds to heat the plasma to 10-20 keV before alpha-particle heating would maintain a self-sustaining burn cycle.

Such power could be provided either in the form of radio-frequency waves (rf heating) or in the form of injected high-energy neutral beams, which would quickly become ionized and hence trapped in the plasma interior (neutral-beam heating).

Furthermore, in the steady-state mode of operation of both tokamaks and tandem mirrors, it will be necessary to provide a steady-state form of radio-frequency (rf) power for special purposes. In tokamaks, steady-state rf power of about 50 MW could be used to produce toroidal currents (current drive) by direct momentum transfer from the waves to the particles or by preferential heating of electrons (see earlier section on Tokamak and Stellarator Magnetic Confinement Systems). In tandem mirrors, steady-state high-frequency microwaves at the multimewatt level will be used to create potential wells or thermal barriers (see section on Magnetic Mirror Systems). In other devices (i.e., bumpy tori), it is necessary to inject high-frequency microwave power at the multimewatt level to produce energetic electron rings (see section on the Elmo Bumpy Torus).

### Radio-Frequency Heating

- Radio-frequency heating utilizes resonant interactions between ions and electrons and externally launched electromagnetic waves of various frequencies to heat the plasma. The technology for generating and launching radio-frequency waves is especially attractive for fusion-reactor applications.



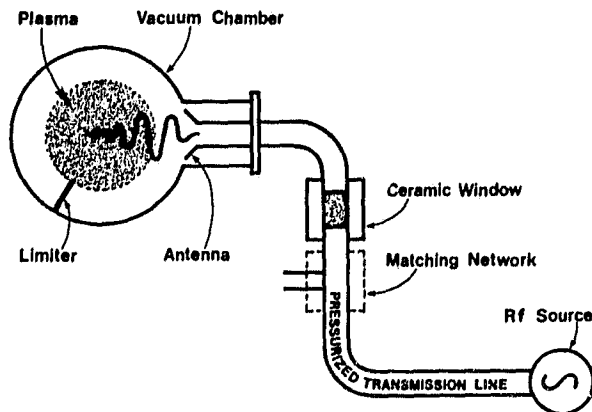


FIGURE 4.16 Schematic illustration of an rf heating system. Typically, the antenna is either a set of current loops or a waveguide array installed through a port in the vacuum chamber.

In Figure 4.16, we show a schematic illustration of an experimental arrangement that may be used for transferring rf power into the plasma. This may be achieved by transmitting rf power from high-power sources via a transmission line to the antenna, which then couples this power to a wave (or waves) that propagates inward and dissipates its energy near the plasma center.

The basic concepts of radio-frequency heating of plasma utilize the interaction between a wave packet that propagates in the plasma and particles that move with velocities that nearly match the phase velocity of the wave. Particles that move slightly slower than the wave absorb energy from the wave, and particles that move slightly faster than the wave transfer energy to the wave. In a thermal distribution of electrons and ions, there are more particles that move slightly slower than the wave than particles that move slightly faster, and therefore a net energy transfer from the wave to the nearly resonant particles takes place. On a slower time scale, the resonant particles transfer the energy gained from the wave to the rest of the particles by collisions. Since the energy confinement time in a reactor-grade plasma (a few seconds) is longer than the collisional energy equilibration time between electrons and ions, and also longer than the collisional slowing-down time of an energetic particle, heating of the whole particle distribution will result. Approximately half of the wave heating techniques rely on this type of interaction (e.g., lower-hybrid heating).

In a magnetized plasma, electrons and ions gyrate in the magnetic

TABLE 4.7 Classification of Frequencies and Power Sources Used for Radio-Frequency Heating

Type of Heating	Typical Frequency	Coupler (Antenna)	Power Source	Available Power/Unit
Electron cyclotron resonance (ECRH)	30-100 GHz	Waveguide or horn	Gyrotron	200 kW; cw at 28 or 60 GHz (1990: 1 MW, 120 GHz)
Lower hybrid (LHH)	1-8 GHz	Waveguide array (grill)	Klystron	0.25-0.5 MW (1 MW; cw possible)
Ion cyclotron resonance (ICRH)	30-200 MHz	Coils (possibly ridged waveguide)	Tubes	0.5-1.0 MW; cw
Alfvén wave	1-10 MHz	Coils in vacuum vessel	Tubes	1 MW; cw

field with their respective gyrofrequencies. If a wave is launched with a frequency equal to the gyrofrequency, then the particles (electrons or ions) see a dc electric field in their own gyrating frame of reference, if the wave has an electric-field component that rotates in the same direction as the particles. This effective dc electric field can then accelerate the particles and transfer net energy to them if they have a thermal distribution. Heating of all particles results after collisional thermalization. In a hot plasma, a similar type of interaction can take place at harmonics of the gyrofrequency, if the finiteness of the wavelength relative to the gyration radius is taken into account. Heating at the fundamental or harmonics of the electron gyrofrequency is called electron cyclotron resonance heating (ECRH) and that at the fundamental or harmonics of the ion gyrofrequency is called ion cyclotron resonance heating (ICRH).

In Table 4.7, we list a range of frequencies and the associated technology to generate the rf power and to launch the waves. The technology will not be discussed here: it is sufficient to say that rf-generating technology is either available or can be developed within the required time scale, in most frequency regimes of interest, to deliver the 50 MW of rf power required in a reactor.

#### MAJOR ADVANCES: THEORY

- Some of the important physics issues on which substantial theoretical progress has been made include (i) propagation and absorp-

tion of the waves in the plasma, (ii) coupling of the launcher (antenna) to the waves in the edge-plasma region, and (iii) nonlinear effects on wave propagation.

While the fundamental theory of wave propagation and absorption was developed in the 1950s and 1960s, many of the applications to wave propagation in the magnetic-field geometries of tokamaks, tandem mirrors, and bumpy tori are being developed only now. Furthermore, theories of wave heating associated with toroidal geometry, absorption of the magnetosonic wave in a two-ion-species plasma, propagation and scattering of the lower-hybrid wave by density fluctuations in a tokamak, propagation and absorption of electron cyclotron waves in a hot dense plasma, and absorption of electron cyclotron waves in a weakly relativistic plasma were developed only recently. Large numerical codes have now been developed that describe the propagation and absorption of electron cyclotron waves, lower-hybrid waves, and magnetosonic waves in a hot plasma in a toroidal or mirror geometry.

Another important area of progress over the past decade has been the development of the theory of wave-antenna coupling, which can predict the wave launching efficiency. This requires a solution of the plasma wave equations in an inhomogeneous medium near the plasma surface and their matching to the fields and currents of the sometimes rather complex wave launching (antenna) structures.

One more subject that deserves attention is the progress made in understanding nonlinear wave phenomena and their effects on wave propagation and antenna coupling. These phenomena include breaking up of large-amplitude launched waves into other waves (parametric instabilities), pushing of the plasma away from the antenna when the wave radiation pressure becomes comparable with the plasma pressure (ponderomotive effect), and trapping of particles by large-amplitude waves (which may be undesirable in some applications).

#### MAJOR ADVANCES: EXPERIMENT

- Experimental results have generally confirmed antenna-coupling theory and theories of wave propagation and absorption. Ion cyclotron heating, using a variety of heating modes, has raised the ion temperature in a tokamak to 3 keV. With lower-hybrid heating, a promising electron-heating regime in tokamaks has been identified. Electron cyclotron heating has been applied successfully to tokamaks and, in mirrors and bumpy tori, has produced hot

TABLE 4.8 Major Ongoing Radio-Frequency Heating Projects

Device	Location	Heating Type	Frequency	Injected Power <sup>a</sup> (MW)	Temperature Rise <sup>b</sup> (keV)	Average Density (10 <sup>13</sup> cm <sup>-3</sup> )	Efficiency <sup>c</sup> (10 <sup>13</sup> keV cm <sup>-3</sup> /MW)
PLT	PPPL	ICRH	42 MHz	3.0 (4.5)	3.5	4	5
TMX-U	LLNL	ICRH	3-5 MHz	0.1 (0.5)	?	?	?
Alcator	MIT	LHH	4-5 MHz	1.0 (2.8)	2.0	13	20
PLT	PPPL	LHH	0.8 (2.5) GHz	0.5 (1.5)	—	—	—
DIII	GA	ECRH	60 GHz	0.3 (1.0)	1.0	3	10
TMX-U	LLNL	ECRH	28 GHz	0.4 (0.8)	30	0.4	?
TFR	France	ICRH	60 MHz	2.2	1.9	10	9
TEXTOR	FRG	ICRH	30 MHz	(3.0)	—	—	—
ASDEX	FRG	ICRH	20-70 MHz	(3.0)	—	—	—
PETULA	France	LHH	1.3 GHz	0.5 (1.0)	0.3	5	3
FT	Italy	LHH	2.5 GHz	0.4 (1.0)	0.5	5	6
ASDEX	FRG	LHH	1.3 GHz	(2.0)	—	—	—
T-10	USSR	ECRH	83 GHz	0.5 (1.0)	1.0	3	6
Heliotron	Japan	ECRH	28 GHz	0.1 (0.2)	0.5	0.4	3

<sup>a</sup> Actual injected power achieved, with potential or planned power in parentheses.<sup>b</sup> Temperature rise is the sum of the increase in central electron and ion temperature during rf heating.<sup>c</sup> Heating efficiency is the product of the temperature rise and the mean density, divided by the injected power.

electron populations with energies of several hundred kiloelectron volts.

During the past decade, significant progress has been made in experimental research on rf wave launching, wave propagation, and plasma heating. Wave-propagation studies on basic research devices, mirror devices, and tokamaks verified the existence, and the dispersion relationship, of most of the waves listed in Table 4.7.

Substantial advances in the plasma parameters achieved in rf heating experiments have also been evident during the past decade. This has been a consequence of a better understanding of the physics of rf heating, improvements in the technology that allowed injection of rf power at the megawatt level, and experimental devices with better particle and energy confinement times. Thus, while in the mid-1970s rf powers injected in any given device were limited to the 0.1-0.2 MW level, and consequently the temperature rise was limited to less than 200 eV, in recent experiments temperature rises in excess of a kiloelectron volt have been produced on injection of about a megawatt of power, at all frequencies of interest. In Table 4.8, we display some of these heating results at the ion cyclotron frequency and its harmonics (ICRH), at or near the lower-hybrid frequency (LHH), and at the electron cyclotron frequency (ECRH). In achieving these results, an understanding of the physics of wave propagation, antenna-wave coupling, and wave absorption has been of crucial importance. It allowed optimization of the antenna design, it helped to determine the optimal location of the antenna, and it identified the best plasma operating regimes for efficient heating.

In the course of these experimental studies, we have discovered the following:

(i) In ECRH (which has been made possible by the development of new high-power sources called gyrotrons), launching from the high-field side of a tokamak plasma (i.e., from inside the torus) is preferred when the temperature is not too high (there is a cut-off layer between the central resonance layer and the edge of the plasma on the low-field side). In large machines, and at high temperatures, launching from the low-field side is acceptable since single-pass absorption becomes efficient.

(ii) For ICRH in tokamaks, magnetosonic wave heating is preferred, and, for heating at the fundamental gyrofrequency, a two-ion species plasma is normally essential for good absorption (otherwise the ions electrostatically shield the ion cyclotron resonance layer). It is preferable to set the frequency to coincide with the gyrofrequency of the

lighter minority species at the center of the device, at least when a low-field-side launch is employed. In this case, an energetic minority component is produced that will transfer its energy to the bulk of the plasma particles by collisions. Launching the wave from the high-field side results in absorption by collective effects at a two-ion hybrid layer, resulting mainly in electron heating. Finally, efficient heating at the second harmonic of the bulk ion gyrofrequency has also been achieved, producing ion temperatures as high as 3 keV.

(iii) In lower-hybrid heating, wave penetration to the ion-plasma-wave resonance region proved to be problematical, resulting in only sporadic and irreproducible ion heating results. However, at frequencies of twice the ion-plasma-wave resonant frequency (or more), good electron absorption and subsequent plasma heating by these waves has been observed.

With respect to experimental techniques, we should also briefly mention the recent results on collective scattering using infrared lasers. The collective scattering of such laser beams from the density fluctuations associated with lower-hybrid waves allows us to track propagation of these waves inside the hot tokamak plasma where probes could not be inserted.

Finally, while most of the rf heating experimental results to date were obtained in tokamaks, important work on ECRH has also been carried out in mirror devices and on bumpy tori. Here, creation of hot electrons with mean energies of several hundred kiloelectron volts have been observed. At present, important ECRH and ICRH experiments are being carried out on the TMX-U tandem mirror at the Lawrence Livermore National Laboratory: ECRH is being used to aid in the formation of the thermal barrier, and ICRH is being tested for heating (and start-up) of the central-cell plasma.

#### PROSPECTS FOR FUTURE ADVANCES

- The rf heating power on existing tokamaks is rapidly being increased to the multimewatt level, and new-generation larger tokamaks will have tens of megawatts of rf power. Radio-frequency power will also be applied increasingly to non-tokamak devices, such as mirrors and stellarators, both for bulk heating and other specialized applications. The theory of rf heating will be advanced by the development of large computer codes—currently in the inception phase—incorporating detailed models of wave propagation and absorption.

In the coming decade, we expect significant advances both in the theoretical understanding of rf heating and in its experimental achievements. While the basic theory of wave propagation and absorption is now well understood, applications to the complex magnetic-field geometries of fusion devices are only in their infancy. At present the best theoretical models employ the geometric-optics approximation and use ray tracing in numerical computations. While this is satisfactory in some cases, the approximations are often not strictly valid, especially near the antenna. Furthermore, in the low-frequency regime (i.e., ICRH and Alfvén-wave frequencies) the wavelengths are often comparable with the density-gradient scale length, and hence an exact solution of the wave equation must be sought. At higher frequencies (ECRH), the wavelengths are short and hence ray-tracing theory is justifiable. However, as the electron temperature increases to reactorlike values, a relativistic theory is necessary.

In tandem-mirror devices, further theoretical work is needed to calculate the distribution function of hot electrons in the thermal barrier. In particular, a relativistic particle kinetic code will be necessary to model the ultra-hot electron population in future devices, such as MFTF-B. These codes will have to be interconnected with realistic transport and ray-tracing codes.

The next decade should also produce new and exciting results in rf heating experiments in all frequency regimes of interest. There are now several rf experiments at the 1-5 MW level throughout the world on existing machines, some of which are listed in Table 4.8. These experiments are aimed at clarifying the physics issues of wave propagation and absorption, and (in the case of tokamaks) at investigating energy and particle confinement times, and impurity injection, under conditions when the rf power significantly exceeds the intrinsic heating power because of the plasma current.

Later in this decade, and in the early 1990s, there will be a number of larger-scale rf heating experiments, now in the planning stage, some of which are listed in Table 4.9. We also expect that further experiments will be proposed for heating of tandem mirrors (i.e., we expect further extension of ICRH and ECRH techniques for start-up, central-cell heating, and thermal-barrier formation).

We can also expect further improvement in rf technology, and this would open up new possibilities with regard to plasma heating. Under consideration is development of (i) megawatt-level klystrons in the lower-hybrid range of frequencies (2-4 GHz), (ii) megawatt-level gyrotrons at frequencies (120 GHz) that would allow ECRH at reactorlike plasma densities, (iii) ultrahigh-frequency gyrotrons

TABLE 4.9 Major Planned Radio-Frequency Heating Experiments

Device	Location	Heating Type	Frequency	Power (MW)	Status
DIII-D	GA	ICRH	60 MHz	20	Proposed
TFTR	PPPL	ICRH	60 MHz	30	Proposed
MFTF-B	LLNL	ICRH	?	?	Proposed
DIII-D	GA	ECRH	60 GHz	2	Approved
MFTF-B	LLNL	ECRH	28-56 GHz	1.6	Approved
JET	EEC	ICRH	25-50 MHz	27	Approved
JT-60	Japan	ICRH	45-90 MHz	3	Approved
Tore-Supra	France	ICRH	70 MHz	6	Approved
JT-60	Japan	LHH	2.0 GHz	10	Approved
FT-U	Italy	LHH	3.7 GHz	8	Approved
Tore-Supra	France	LHH	3.7 GHz	8	Approved
T-15	USSR	ECRH	86 GHz	5	Approved

(140-200 GHz) suitable for high-field devices, and (iv) development of multimewatt tubes (60 MHz) that would greatly simplify high-power ICRH technology.

#### Radio-Frequency Current Drive

- The use of radio-frequency waves to drive currents in tokamaks, typically by imparting momentum to electrons, is of enormous potential benefit, since it permits the tokamak to operate steady-state.

Current drive refers to a process—of interest mainly in tokamaks—for maintaining a current in a plasma by means other than transformer-induced electric fields. One of the most important areas of progress in the entire field of tokamak research has been the theoretical prediction and experimental demonstration of the feasibility of driving steady-state currents by radio-frequency waves. This would allow the possibility of replacing the transformer-driven pulsed toroidal current by an rf-driven steady-state toroidal current. (Current drive by neutral beams is also possible but requires very energetic beams and has somewhat lower efficiency.)

In its simplest form, current drive involves a direct momentum transfer from waves to electrons. However, current generation by



preferential heating of electrons moving in one toroidal direction may be just as efficient as that by direct momentum transfer, and therefore essentially all waves in Table 4.8, not just those that have large toroidal wave momentum, may be utilized for current generation.

#### MAJOR ADVANCES: THEORY

- Recent theoretical calculations of rf current-drive efficiency have shown that the current-drive power required for a steady-state tokamak reactor should be acceptable. Various quasi-steady-state schemes offer the prospect of even better efficiency.

Although there have been many theoretical ideas regarding current drive ever since the tokamak concept was proven to be viable, it is only recently that current-drive theories have been put on a more rigorous basis. In particular, it was shown in 1978 that rf-current drive in the lower-hybrid frequency regime may be sufficiently efficient to be of practical interest in a fusion reactor. Since then, current-drive efficiencies (driven current divided by rf power) have also been evaluated for most of the other waves that propagate in a plasma. The efficiency varies inversely with plasma density.

Although this efficiency varies from wave to wave, it is generally found that, in a reactor, 10 percent or more of the fusion power produced would be needed to generate the rf power required to maintain the toroidal current. Specifically, at least 50 MW of rf power would be required to maintain about 5 MA of steady-state toroidal current. An ingenious quasi-steady-state variation of this technique—resulting in higher overall efficiency—may also be possible by ramping up the current periodically by rf, hence “recharging” the transformer; the density may be reduced during this time. Subsequently, in the high-density phase, the transformer may be used to maintain the current for several hours to ensure a quasi-steady burn cycle.

#### MAJOR ADVANCES: EXPERIMENT

- Recent experiments using lower-hybrid waves have confirmed the theory of rf-current drive, and have succeeded in sustaining tokamak currents for pulse durations of several seconds. Both current-drive efficiency and lower-hybrid-wave penetration are found to decrease at high plasma density, as predicted theoretically.

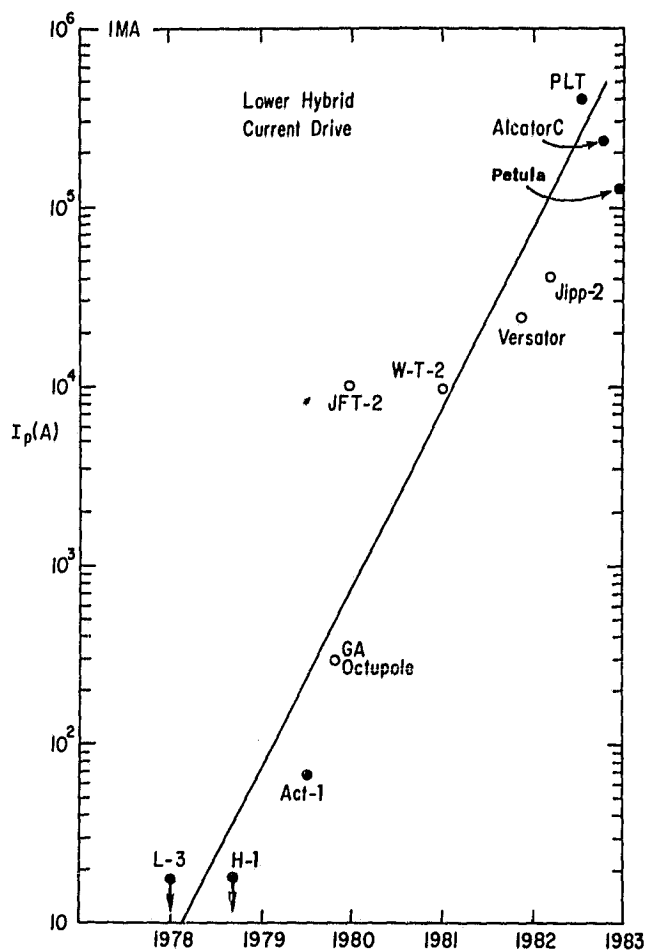


FIGURE 4.17 Progress in lower hybrid current drive in tokamaks. In PLT at Princeton and Alcator C at MIT, the plasma current has been sustained for a second or longer without any applied voltage.

The experimental verification of theoretical predictions of lower-hybrid current drive has been one of the most exciting and productive developments in recent tokamak research. While 5 years ago the maximum rf-driven currents amounted to only a few milliamperes, today rf currents up to 400 kA have been generated in tokamaks (see Figure 4.17). The first current-drive demonstrations at the 20-kA level were in the small Versator tokamak at MIT. The most advanced among

today's experiments are the 800-MHz, 0.5-MW PLT experiment and the 4.6-GHz, 1-MW Alcator C experiment. Some of the exciting results include maintenance of the toroidal current by the rf power for time durations up to 3.5 s (PLT) and driving currents at densities up to  $10^{14}$  particles per cubic centimeter (Alcator C).

In several experiments (i.e., Alcator C and PLT), the high-energy x-ray spectra were measured before and after application of the rf power. It was shown that a high-energy electron population formed on application of the rf power. In agreement with theoretical predictions, it is this asymmetric suprathermal electron population that is responsible for the toroidal current generation.

One of the questions that current-drive experiments must answer is the current-drive efficiency, namely, current generated divided by power absorbed. The parameter  $nIR/P$ , where  $n$  is the average density,  $I$  is the total toroidal current,  $R$  is the major radius, and  $P$  is the total power, is plotted in Figure 4.18 versus the plasma electron temperature for a number of devices. If this could be extrapolated to the reactor regime, we would need at most 50 MW of circulating rf power to drive 5 MA of toroidal current. However, theory predicts that, under reactorlike conditions, the present lower-hybrid waves will be less

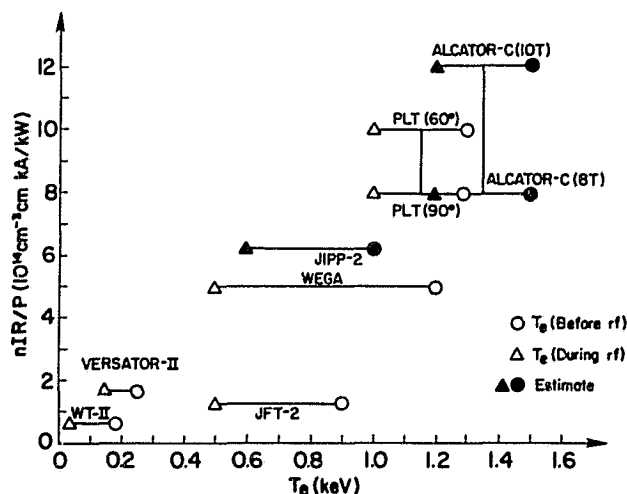


FIGURE 4.18 Measured lower-hybrid current-drive efficiency. Theory predicts that the efficiency (current  $I$  divided by rf power  $P$ ) should scale inversely with plasma density  $n$  and major radius  $R$  and should improve with increasing energy of the current-carrying electrons. To show that this relationship is verified, we plot the quantity  $nIR/P$  versus electron temperature  $T_e$  from a number of different experiments.

efficient in penetrating the plasma, and other waves (such as the Alfvén wave or the magnetosonic wave) may have to be used for current drive. The present lower-hybrid waves should, however, be satisfactory for the quasi-steady-state mode of current-drive operation.

#### PROSPECTS FOR FUTURE ADVANCES

- Lower-hybrid current drive will be tested at reactorlike plasma parameters in large tokamaks. Radio-frequency current drive using other waves with better penetration characteristics will be explored.

The next decade should produce important advances in rf current-drive experiments, in regard to the magnitude of the driven current, the duration of the current pulse, and the number of different rf techniques that are employed. There are several lower-hybrid current-drive experiments that are ongoing now, are being increased in power, or are being initiated in the near future on existing tokamak devices (see Table 4.8). These experiments will extend the measurements of current drive efficiency further toward the reactor regime and will determine the best compromise between transformer and rf current drive for providing efficient quasi-steady-state operation. By the end of the decade, there will be some much-larger-scale current-drive experiments in operation, as indicated in Table 4.9. (Note that lower-hybrid experiments can be employed both for heating and current drive.)

There are also plans on present experimental devices to explore the use of other waves for current drive, in particular the magnetosonic wave and the electron cyclotron waves—the latter in combination with lower-hybrid waves to impart momentum to the hot electrons.

#### Neutral-Beam Heating

- Neutral-beam heating utilizes neutralized beams of accelerated hydrogenic ions, which are injected into the plasma. Neutral-beam heating has been particularly successful in producing reactorlike ion temperatures in tokamaks and mirrors.

In the past, high-power neutral-beam heating has been the leading technique for delivering large quantities of heating power to both tokamak and mirror plasmas. The physics of neutral-beam heating is relatively simple as compared with radio-frequency heating. Beams of neutral atoms are created by accelerating ions (usually hydrogen or deuterium) extracted from a discharge plasma source by means of a

carefully designed grid system. The ions are accelerated to energies of 20-120 keV and focused into a directed beam that then passes through a neutralizer chamber filled with gas at low pressure. Here, a large fraction of the ions recapture electrons from the gas atoms, and a high-energy (20-120 keV) beam of neutral atoms is formed. These neutral beams are then injected through several large pumped ports of a fusion device. Subsequently, the neutral beam penetrates into the plasma interior unhindered by the magnetic field, until the neutral atoms are reionized by the plasma already present. Once reionized, the high-energy ions are captured by the magnetic bottle, and collisional thermalization on the bulk ions and electrons follows.

Because of the high energies of the beam ions, megawatts of power can be delivered for beam currents of a few tens of amperes. Such sources have been developed by the Oak Ridge National Laboratory and the Lawrence Berkeley National Laboratory.

#### MAJOR ADVANCES

- Neutral-beam heating has been the key to the most notable achievements of the past decade in tokamaks and mirrors—high ion temperatures, high plasma beta, and tandem-mirror confinement.

Table 4.10 summarizes the beam energies, powers, and pulse lengths that have been achieved and indicates the most significant results that neutral-beam heating has produced for the fusion program. The most spectacular results so far have been achieved on PLT and PDX, where beam heating raised the central ion temperature from 1 keV to about 7 keV, and on Doublet III, where beam heating resulted in an average beta of a record 4.6 percent. Neutral-beam heating has also been used in TMX to demonstrate the principles of tandem-mirror confinement.

In most beam-heating experiments in tokamaks so far, the deposition of the injected beam, the beam-ion slowing-down process, and the confinement of the fast ions were found to be essentially classical, i.e., determined by simple physical processes of interparticle collisions. Accordingly, the physics of the neutral-beam injection process itself can be said to be well understood. However, it has been found that, as the injected beam power exceeds a few megawatts (a few times larger than the heating power due to the plasma current), the energy confinement time deteriorates by a factor of 2-5. At present, it is not known whether these results are a consequence of plasma beta or tokamak geometry, in which case rf heating may be equally susceptible

TABLE 4.10 Neutral-Beam Parameters and Major Program Contributions

Device	Location	Type	Year	Beam Energy (keV)	Beam Power (MW)	Pulse Length (ms)	Major Program Contribution
ATC	PPPL	Tokamak	1974	15	0.1	10	NB + Compression
ORMAK	ORNL	Tokamak	1976	30	0.4	50	First High-Power NB
PLT	PPPL	Tokamak	1978	40	2.5	150	$T_i = 6.5$ keV
2XIIB	LLNL	Mirror	1979	18	7.0	10	Mirror $\beta = 45\%$
TMX	LLNL	Tandem	1980	20-40	5.0	25	Tandem Confinement
ISX-B	ORNL	Tokamak	1981	40	2.5	100	$\beta$ Saturation
PDX	PPPL	Tokamak	1982	50	7.0	150	$\beta = 3\%$ (circ.)
DIII	GA	Tokamak	1982	70	3.0	250	$\beta = 4.6\%$ (noncirc.)
TFR	France	Tokamak	1976	35	0.5	50	
T-11	USSR	Tokamak	1978	35	0.5	30	
WVII-A	FRG	Stellarator	1980	25	1.0	150	Stellarator Confinement
ASDEX	FRG	Tokamak	1982	40	3.0	200	Diverter, H-mode

to such deterioration when comparable power levels are achieved, or whether it is caused specifically by the neutral-beam heating technique.

#### PROSPECTS FOR FUTURE ADVANCES

- Next-generation neutral-beam systems for tokamak and mirror applications will have higher beam energy and greatly increased pulse length. However, neutral-beam systems for tokamak reactor application would need even higher beam energy, necessitating the successful eventual development of negative-ion beams.

In Figure 4.19, we show neutral-beam powers that have been delivered into past and present machines and also the projected beam powers during the next few years. We see that rather large powers are expected to be delivered in the upcoming DIII-D, TFTR, and MFTF-B

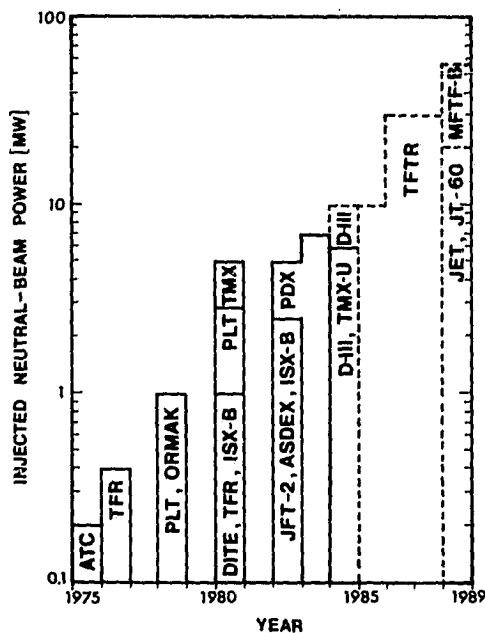


FIGURE 4.19 Progress in neutral-beam heating. We show the neutral-beam power injected into various tokamak and mirror devices; actual achievements are shown with solid lines; systems under construction are shown with dashed lines. (In the case of JET, we show the total power, which will be partly neutral beam and partly rf).

devices (i.e., up to 30 MW of beam power will be injected into TFTR, and up to 60 MW will be injected into MFTF-B).

The beam energies in these next-generation neutral-beam systems will be in the range of 80-160 keV. The pulse lengths will also be substantially greater than in present-day systems (specifically, 1.5 s on TFTR, 10 s on JET and JT-60, and 30 s on MFTF-B). There is widespread confidence that these systems will be successful in heating plasmas to reactorlike energy densities.

While neutral-beam heating technology has achieved outstanding progress in the past, and has succeeded in providing the large powers needed to heat the present generation of machines, its future beyond 1990 is less certain. There are two basic problems that have to be overcome:

(i) The pulse length of present-day injectors has until recently been limited to about a second. Running beam sources for times longer than that causes serious deterioration of the filaments inside the beam sources. This may be remedied either by using indirectly heated cathodes or by using rf plasma sources for the beam ions. For the MFTF-B neutral-beam system, it is encouraging to note that, using an indirectly heated cathode, both Oak Ridge National Laboratory and Lawrence Berkeley Laboratory have developed 80-keV, 80-A beams that have been run for a 30-s pulse duration. Nonetheless, in the next few years significant technological advances will have to be achieved to provide the beams necessary for achieving the full potential of devices such as MFTF-B.

(ii) In the present generation of devices, beam energies of 100-150 keV are satisfactory, but in reactor-size devices beam energies of about 500-keV energies may be necessary. The neutralization cross section of positive-ion beams falls rapidly above energies of about 75 keV for protons and 150 keV for deuterons; hence, to provide efficient neutral beams with energies of about 500 keV, negative-ion beams will have to be developed whose ionization cross section is more favorable.

Nevertheless, neutral-beam heating has certain advantages. The capability for fueling the plasma center may be unique to neutral beams, and is particularly important for mirror reactors.

Table 4.11 presents projections of requirements for neutral-beam systems in fusion reactors. Because of the very high beam energies needed in reactor-size tokamaks, neutral-beam heating is currently viewed as a backup to radio-frequency heating for tokamak applications. For mirror reactor applications, no alternative to neutral beams has been established for creating the necessary confining potentials.



TABLE 4.11 Projected Requirements for Neutral Beams in Reactors

Reactor Concept	Application	Beam Energy (keV)	Beam Power (MW)	Pulse Length (s)
Pulsed tokamak	Heating to ignition	400	30-50	10-50
Pulsed tokamak	Pulsed current drive	400	$\leq 30$	100
Steady-state tokamak	Continuous current drive	1000	$\geq 50$	Continuous
Tandem mirror <sup>a</sup>	Central cell heating and fueling	200	50 <sup>b</sup>	Continuous
Tandem mirror <sup>a</sup>	End plug potential	500	10	Continuous
Stellarator	Heating to ignition	400	50	10-50

<sup>a</sup> Tandem-mirror requirements assume 50 MW of ECH power for the thermal barrier.

<sup>b</sup> Central-cell power may be reduced to 10 MW during start-up in the case of an ignited central cell in a thermal-barrier tandem mirror.

The neutral-beam systems employed in present and next-generation devices are all based on neutralizing hydrogen-isotope positive-ion beams. The high beam energies needed for a reactor dictate development of a new approach to beam-ion sources, namely, by using negative ions. Several promising concepts of negative-ion sources have been recently operated at about 1 A using hydrogen. This must be raised to the level of about 10 A. Acceleration of the ions to 400 keV or more is likely to require technologies other than the high-gradient, electrostatic accelerators now used in the positive-ion systems. A promising candidate is the strong-focusing, low-gradient dc accelerator. For best power efficiency, development of a neutralizer based on the photodetachment of the negative ion's loosely bound electron by laser beams is at least desirable, and possibly necessary.

## INERTIAL-CONFINEMENT FUSION SYSTEMS

### Introduction

- The inertial-confinement approach to fusion is based on compressing thermonuclear fuel to extremely high density and heating it to temperatures high enough that the fuel ignites and burns before the compressed mass has time to disassemble.

Inertial-confinement fusion complements the magnetic-confinement schemes and represents an independent approach based on quite

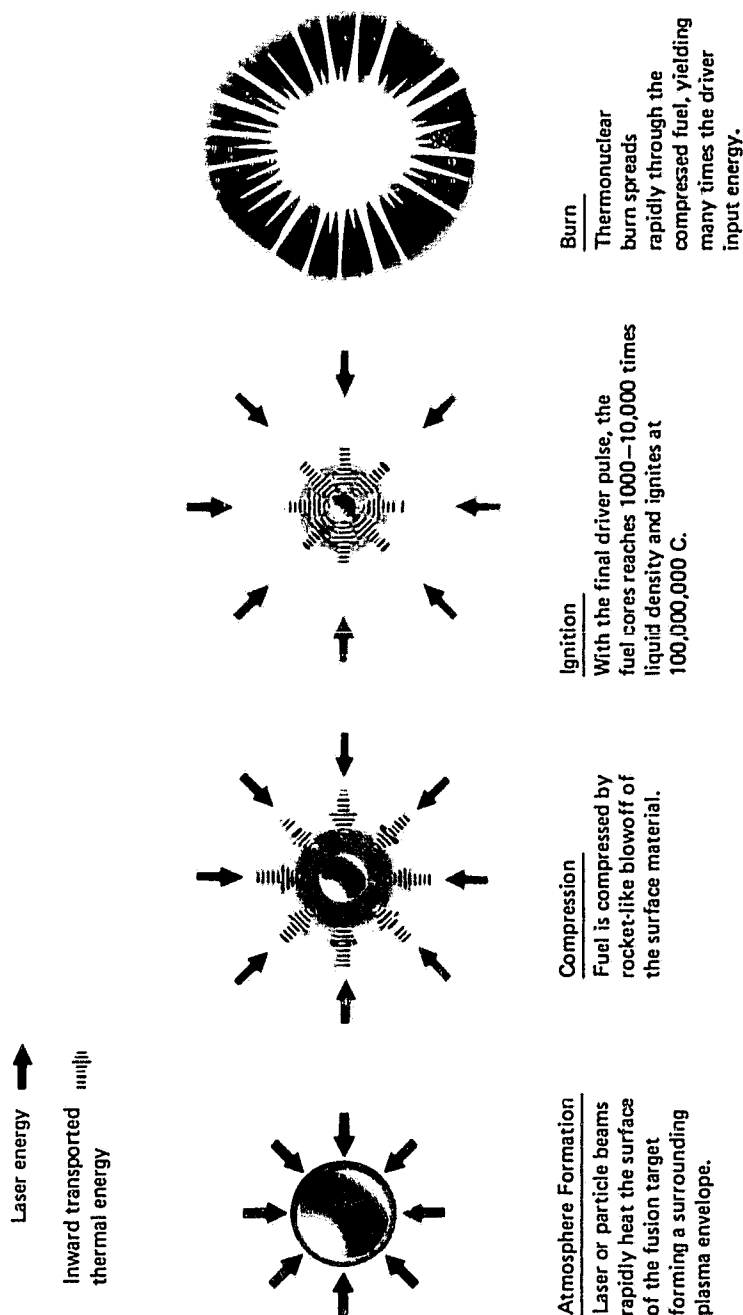


FIGURE 4.20 Schematic illustration of the inertial-confinement fusion concept. An ultrahigh-power laser beam implodes a tiny D-T pellet, which reacts and burns before it has time to disassemble.

different physical principles. Instead of magnetically confining hot plasmas with densities of  $10^{14}$  to  $10^{15}$  particles per cubic centimeter for times of up to a second, fuel is imploded to a very high density, typically  $10^{25}$  to  $10^{26}$  particles per cubic centimeter, and burned in tens of picoseconds (1 picosecond equals one trillionth of a second, i.e.,  $10^{-12}$  s) while inertially confined. For ultimate commercial applications, inertial-confinement fusion has the very desirable feature that the driver facility and reactor chamber can be well separated from one another. This separation greatly reduces the technological problems of practical reactor-chamber design.

Inertial-confinement research also has many other applications related to the physics of high-energy density. The irradiation of plasmas by intense laser light allows the study of many nonlinear processes with applications throughout plasma physics. The generation of pressures of tens to hundreds of megabars (1 megabar equals a million atmospheres) allows the investigation of matter under very high pressures. The generation of highly ionized matter and of intense short pulses of x rays allows the study of atomic physics of importance in the development of x-ray lasers.

Inertial fusion works by focusing an intense beam of laser light or particles onto the outer layers of a spherical shell encapsulating fusion fuel, as illustrated in Figure 4.20. The fuel is then compressed by pressures of tens to hundreds of millions of atmospheres generated by the rocketlike blowoff of the surface material. At the end of the driver pulse, when the fuel reaches about 1000 times liquid density, a portion in the center ignites at a temperature of about a hundred million degrees Celsius. The thermonuclear burn spreads rapidly through the remaining compressed fuel, yielding many times the driver energy. The high fuel density increases the thermonuclear reaction rate to allow the fuel to burn while it remains together by its own inertia. Energy is released in the form of energetic neutrons, x rays, and helium nuclei, which are captured and converted to thermal energy for various applications. For power generation, pellet gains of a hundred or more are needed to compensate for reactor and driver inefficiencies, whereas other applications, such as hybrid reactors and fissile-fuel production, are feasible with lower pellet gains.

In the past decade, a vigorous effort has been undertaken to investigate the physical principles of the inertial-confinement approach. The physical constraints that need to be satisfied for inertial fusion to succeed can be divided into five critical elements:

- *Coupling Efficiency.* The fraction of driver energy utilized for fuel

compression and ignition needs to be high; efficiencies of about 5 percent are needed for high-gain applications.

- *Cold Compressed Fuel.* The fuel must remain nearly isentropic (cold) during pellet implosion, in order to achieve high final fuel densities at low driver energy cost; an energy increase of only a few times the minimum (Fermi degenerate) level is permissible.

- *Ablation Pressure.* Sufficient ablation pressure needs to be developed at the pellet surface to achieve high-density compression and to avoid hydrodynamic instability; pressures from tens to hundreds of megabars are needed.

- *Implosion Symmetry.* The pellet must be imploded uniformly to minimize the volume of hot fuel needed to ignite the pellet and to avoid hydrodynamic destruction of the pellet; implosion uniformities of close to 1 percent may be needed.

- *Ignition Concept.* A practical means by which a small volume within the pellet's fuel can be ignited, and the remaining fuel consumed by propagating burn, needs to be established; the central hot spot must have temperatures above about 4 keV and have a density-radius product of about 0.3 gram per square centimeter. The remaining fuel should have a density-radius product of about 3 grams per square centimeter for efficient burn.

Inertial-confinement fusion research in the United States is conducted mainly at the Lawrence Livermore National Laboratory, Livermore, California, and at the Los Alamos National Laboratory, Los Alamos, New Mexico. Smaller programs are under way at the Naval Research Laboratory, Washington, D.C.; at KMS Fusion Inc., Ann Arbor, Michigan; at the University of Rochester, Rochester, New York; and at Sandia National Laboratories, Albuquerque, New Mexico. In addition, a number of universities contribute to inertial-confinement research.

### Major Advances

#### DRIVERS FOR INERTIAL-CONFINEMENT FUSION

- An impressive array of experimental facilities for inertial-confinement research has been developed over the past decade. Neodymium-glass lasers have been constructed with output energies of up to 30 kJ and powers up to 25 terawatts [1 terawatt (TW) equals  $10^{12}$  watts]; CO<sub>2</sub>-lasers have been constructed with 30 to 40 kJ of output energy and powers up to 30 to 40 TW. Light-ion

beams have been generated with up to hundreds of kilojoules of output energies at several terawatts of power.

Table 4.12 lists the major driver facilities for inertial-confinement research, both existing and under construction, worldwide. In addition, several heavy-ion drivers have also been proposed for construction at the Lawrence Berkeley Laboratory and in West Germany. Ultimately, for power-generation purposes, the driver must be highly efficient (about 10 percent), reliable, and capable of being repetitively pulsed.

TABLE 4.12 Major Inertial-Confinement Fusion Facilities

Facility	Location	Driver Type	Energy <sup>a</sup> (kJ)	Power <sup>a</sup> (TW)
NOVA	LLNL	Nd-glass	(100)	(125)
NOVETTE	LLNL	Nd-glass	30	25
PHAROS-III	NRL	Nd-glass	(2)	(4)
PHAROS-II	NRL	Nd-glass	1	2
OMEGA	Rochester	Nd-glass	4	12
GDL	Rochester	Nd-glass	0.1	0.5
CHROMA-I	KMSF	Nd-glass	1	2
ANTARES	LANL	CO <sub>2</sub>	(30-40)	(30-40)
HELIOS	LANL	CO <sub>2</sub>	5-10	10-20
LAM	LANL	KrF	(10-20)	—
RAPIER B	LLNL	KrF	0.8	—
PBFA-II	Sandia	Light ion	(4000)	100
PBFA-I	Sandia	Light ion	1000	20
GAMBLE-II	NRL	Light ion	100	2
PHEBUS	France	Nd-glass	(30)	(25)
OCTAL	France	Nd-glass	4	4
GEKKO XII	Japan	Nd-glass	(20)	(40)
GEKKO IV	Japan	Nd-glass	2	4
HELEN	UK	Nd-glass	1	3
VULCAN	UK	Nd-glass	1	2
DELFIN	USSR	Nd-glass	5	2-7
UMI-35	USSR	Nd-glass	8-10	4-6
LEKKO III	Japan	CO <sub>2</sub>	10	10
LEKKO II	Japan	CO <sub>2</sub>	0.5	0.5
REIDEN IV	Japan	Light ion	50	1
KALIF	FRG	Light ion	75	2

<sup>a</sup> For laser, energy quoted reflects performance at long pulse. Power quoted reflects performance at short pulse. For light ions, energy and power quoted are those delivered to the ion diode. Account is not taken of ion production and transport efficiency, which reduce these numbers by up to a factor of 4. Parameters in parentheses denote facilities under construction.

The most useful driver for inertial-fusion research to date has been the laser. Powerful laser-light pulses can be focused down to the small dimensions required to generate high pressures on a pellet surface, their pulse length and shape can be varied, and their wavelength controlled. In short, they make excellent research tools to investigate inertial-confinement physics and to test pellet concepts. The dominant lasers for inertial-fusion research have been the neodymium-glass laser, which produces light pulses in the near-infrared portion of the spectrum [1.05 micrometers; 1 micrometer ( $\mu\text{m}$ ) equals  $10^{-6}$  meter], and the  $\text{CO}_2$ -gas laser, which operates in the far-infrared (10.6  $\mu\text{m}$ ). Neodymium-glass lasers have achieved powers on target up to 25 TW, and  $\text{CO}_2$  lasers have achieved powers in the 30-40 TW range. The neodymium-glass laser has proven to be a particularly flexible tool, since its output can be efficiently frequency converted. If short-wavelength light proves to be preferable for inertial fusion, then a krypton-fluoride laser, an excimer system (0.25  $\mu\text{m}$ ) with good efficiency, is an attractive candidate.

In addition to lasers, intense particle beams can be used as inertial-confinement pellet drivers. There are currently two main approaches to particle-beam inertial fusion: light ions and heavy ions. Light ions, such as protons, lithium, or carbon ions, are generated in high-current pulsed power accelerators, which provide megaamperes of ion current at a few megavolts of energy. Light-ion-beam generators are highly efficient and relatively inexpensive but cannot as yet attain the power densities required for fusion. The heavy-ion approach would use very heavy ions, such as lead ions accelerated up to gigaelectron-volt energies (a gigaelectron volt equals a billion or  $10^9$  electron volts) in conventional high-energy accelerators. Accelerators needed to supply such beams for inertial fusion would be expensive but would have many properties desirable for inertial-fusion reactors; they could provide highly efficient, repeatedly pulsable, and focusable beams.

Although particle beams may one day be the preferred driver for inertial fusion, their technology has not yet advanced to the stage where they can be used for extensive inertial-fusion research involving targets. Therefore, we will concentrate here on describing inertial-fusion research using a laser driver.

#### LASER-TARGET PHYSICS

- Using a neodymium-glass laser driver, targets have been imploded to about 100 times liquid density—within a factor of 10 of reactor

requirements. The development of increasingly sophisticated plasma instrumentation and modeling codes has led to improved agreement between the experiments and the theory of laser-target interaction.

With these experimental facilities, a great deal of progress in inertial-confinement research has been made. The coupling of laser light with targets has been characterized over a wide range of laser intensity and wavelength. Numerous coupling processes, ranging from collisional absorption to collective plasma processes, have been confirmed and quantified. A regime of excellent coupling for laser light with wavelengths of less than  $1\text{ }\mu\text{m}$  has been demonstrated.

D-T fuel in glass microballoons has been heated to thermonuclear temperatures. Targets and shells have been ablatively accelerated to above  $10^7\text{ cm/s}$  with velocity nonuniformities below 5 percent. D-T fuel has been imploded to a final fuel density of about a hundred times its liquid density, with fuel temperatures of about 400 eV. These compressions are within a factor of about 10 of the compression needed for a reactor target.

Instrumentation to measure the properties of the beam-target interaction has evolved at a remarkable pace in the last decade. Typically, quite extreme ranges of plasma conditions are encountered in a single inertial-confinement experiment: the density ranges downward from 1000 times solid density to near vacuum; the temperature ranges in some cases from 1 eV to beyond  $10^5\text{ eV}$ ; the electromagnetic radiation emitted extends from the infrared region into the gamma-ray region; and various ion and electron populations may be present with energies from electron volts to millions of electron volts. Moreover, experiments often need to be made with micrometer spatial resolution and picosecond temporal resolution. Diagnostics now exist that can measure many of these properties; they have, in large measure, been instrumental in the many significant advances that have been made recently in understanding the laser-target interaction.

Equally important, theory and large simulation codes have advanced toward the goal of providing a predictive capability for new irradiation conditions. These theoretical tools have guided the advances made in the experiments and have, in turn, been improved through constant comparison with these experiments. New target design concepts have been developed. New designs based on the hohlraum approach rely on x rays from driver-produced plasmas to implode the target.

### Current Frontiers of Research

#### LASER-PLASMA COUPLING

- The absorption of laser light occurs in a corona plasma surrounding the target. Experiments have generally confirmed both the collisional absorption mechanism and the theoretically predicted collective plasma effects on laser-light coupling. The experiments have also demonstrated a large increase in collisional absorption concomitant with a large decrease in deleterious collective effects as the wavelength of the laser light is decreased.

In laser fusion, a target is irradiated with an intense pulse of laser light. For high-gain targets, the required intensity will be in the range of  $10^{14}$  to  $3 \times 10^{15}$  watts per square centimeter ( $\text{W}/\text{cm}^2$ ), depending on the details of the target design, and the pulse length will be of order 10 nanoseconds [1 nanosecond (ns) equals one billionth of a second, i.e.,  $10^{-9}$  s]. Very early in the pulse (at intensities about  $10^{10}$   $\text{W}/\text{cm}^2$ ), the surface of the target breaks down, forming a plasma. As is well known, light will only propagate in a plasma up to a maximum density, the critical density, given by the condition that the electron plasma frequency equals the laser light frequency. The critical densities are about  $10^{21}$  and  $10^{19}$  particles per cubic centimeter, for the neodymium-glass laser and  $\text{CO}_2$  laser, respectively. Some experiments have also been carried out using crystals to double, triple, and quadruple the frequency of a neodymium-glass laser, and the critical densities are then correspondingly higher. The critical densities are much less than solid density, and so the laser light absorption takes place in a relatively low-density "corona" plasma surrounding the irradiated target.

The coupling of the laser light to this plasma is clearly one of the fundamental issues in laser fusion. Obviously, the absorption efficiency of the laser light needs to be high to maximize the efficiency of the driver. However, the heated electron velocity distributions are crucial also, because very-high-energy electrons have a relatively long range and can penetrate into, and preheat, the fuel within the interior of the target. Even modest preheat will prevent the D-T fuel from reaching the density compression required for high-gain targets.

Inverse bremsstrahlung, or collisional absorption, is the preferred laser-wave absorption mechanism. Physically, inverse bremsstrahlung is due to collisions between the electrons, which are being vibrated by the electric field in the light wave, and the background plasma ions.



The laser absorption rate is proportional to plasma density and inversely dependent on electron temperature. Collisional absorption thus becomes more efficient as the wavelength of the laser light is decreased, since the light can propagate into denser, relatively cooler plasma. Furthermore, since the collision frequency between electrons and ions has a strong inverse dependence on the electron velocity, slower particles are preferentially heated. Hence, favorable electron distributions are generated.

There are many other mechanisms for laser-plasma coupling. These mechanisms arise from the excitation of plasma waves by the intense laser light. The waves, in turn, can heat the plasma particles or scatter the incident light. Heating of the plasma by excited plasma waves is often undesirable, since suprathermal electrons can be generated. The fast electrons originate because electron plasma waves propagate with high phase velocities, and electrons in near resonance with these waves will be preferentially energized. Suprathermal electrons can provide preheat, an effect to be avoided.

The simplest absorption process involving electron plasma wave heating is resonance absorption. Whenever the laser-light electric field oscillates electrons across a spatial variation in density, a high-frequency charge-density fluctuation is driven. This density fluctuation resonantly excites an electron plasma wave at the critical density.

In addition, electron plasma waves and ion acoustic waves can be excited by a variety of plasma-wave instabilities driven by the intense laser light. Most of these instabilities can be simply characterized as the resonant decay of the incident light wave into two other waves. Given that the plasma supports electron plasma waves, ion acoustic waves, and light waves, the possibilities are straightforward to list. There is parametric decay, namely decay into an electron plasma wave and an ion acoustic wave, which occurs near the critical density. The two-plasmon instability, namely decay into two electron plasma waves, occurs near one fourth of the critical density. The Raman instability, namely decay into a scattered light wave and an electron plasma wave, is a process that operates for densities even below one fourth of the critical density. These instabilities all generate an electron plasma wave and are a fuel-preheat threat. In addition, the Brillouin instability, namely decay into a scattered light wave and an ion acoustic wave, occurs throughout the underdense plasma and can scatter the light before absorption. Finally, there are self-focusing instabilities. A small hot-spot enhancement of the intensity of the incident light wave creates a density depression, either by pushing the plasma aside via the enhanced field pressure or by enhanced heating

and subsequent plasma expansion. Since a light wave locally refracts into lower-density plasma, the density depression leads to a further enhancement of the hot spot, giving rise to intense filaments.

In addition to instabilities driven directly by the laser light, many other important processes can occur in laser-irradiated targets. For example, ion turbulence and self-generated magnetic fields can be created in the interaction process. Magnetic fields can be as high as several megagauss, sufficiently large to impede the heat flow or to introduce new kinds of magnetically driven fluctuations.

Figure 4.21 presents a simplified summary of the many different processes operative in the underdense plasma. Virtually every coupling mechanism indicated in Figure 4.21 has now been observed in experiments. Important features that have been observed include generation of energetic electrons associated both with resonance absorption and with the various instabilities producing electron plasma waves and scattered light associated with the Brillouin and Raman instabilities. Most important, the experiments have demonstrated a strong increase in collisional absorption concomitant with a strong decrease in deleterious collective effects (hot-electron generation and light scattering) as the wavelength of the laser light is decreased.

Figure 4.22 shows the absorption efficiency as a function of laser intensity for a variety of wavelengths ranging from 1.05 to 0.26  $\mu\text{m}$ . The scaling with wavelength has had a strong impact on laser fusion research. Most large laser facilities now planned will operate at wavelengths of half a micrometer or less.

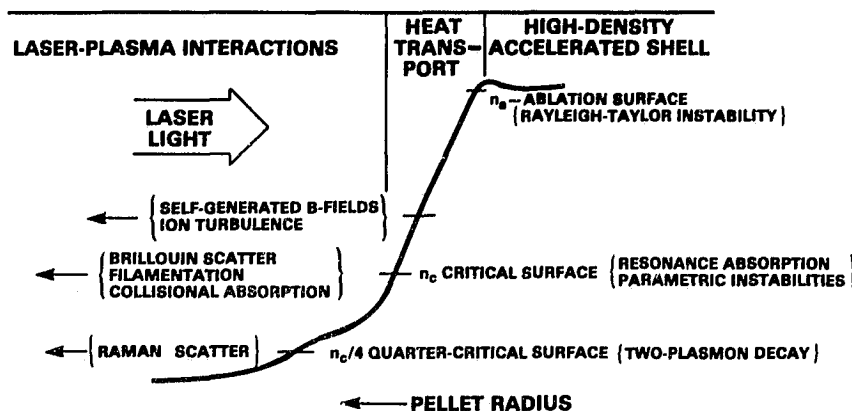


FIGURE 4.21 Regions of occurrence of various laser-plasma coupling processes, heat transport, and ablation, shown on the pellet density profile.

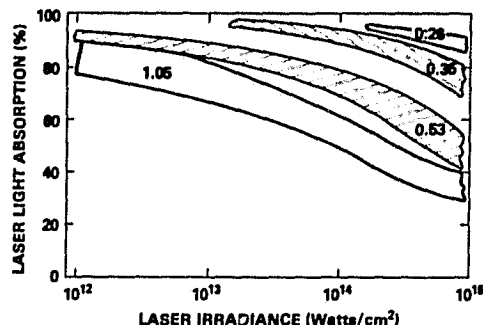


FIGURE 4.22 Experimental results on laser-light absorption in percent versus laser intensity for various laser wavelengths. Results are given for laser wavelengths, which are shown in micrometers ( $\mu\text{m}$ ). Note the better absorption with shorter wavelength.

Research on laser-plasma coupling continues to contribute to the understanding of many fundamental processes in plasma heating and turbulence. It is important to extend this research to the much larger-scale plasmas that will be encountered in reactor targets. The present understanding of the various coupling processes and detailed plasma conditions in larger-scale plasmas is inadequate to make quantitative predictions with confidence.

#### HEAT TRANSPORT AND ABLATION

- After the laser-light energy has been deposited, it must be efficiently-transported inward, to an ablation surface, within which the pellet implodes. Short-wavelength laser light improves heat transport efficiency but may lead to greater nonuniformities in the implosion.

In the direct-illumination approach to inertial-confinement fusion, the laser-heated electrons are dominant in transporting energy to an ablation surface, as shown in Figure 4.21. Outside the ablation surface the target material is stripped away from the pellet shell by the heat wave. As this ablating material is accelerated outward toward the laser, it creates a large rocketlike ablation pressure, which accelerates the remaining shell inward and compresses the fusion fuel.

Transport of the intense electron energy fluxes characteristic of laser-fusion applications is itself an important topic in applied plasma physics. The usual theory of diffusive heat flow of electrons is in general inadequate, and improved theories are now emerging. In

addition, the flow of electrons can be markedly reduced by self-generated magnetic fields created by anisotropies in the energy deposition. Fortunately, the effects of such fields are much reduced when targets are more uniformly irradiated.

The heat flow has been investigated in laser plasma experiments under a wide variety of conditions. Often, the experiments have indicated a heat flow below the classical level. Empirical heat-flow models, normalized to experiments, are often used in design calculations. Since electron heat transport has a marked effect on plasma conditions, hydrodynamic efficiency, preheat, and implosion symmetry, this remains a key area for further research.

The efficiency by which absorbed energy reaches the ablation surface and the resulting blow-off velocity of the ablating materials determine the hydrodynamic efficiency of the pellet, that is, the kinetic energy delivered to the fuel divided by the absorbed driver energy. The most efficient transfer of momentum to the pellet shell occurs when the blow-off plasma velocity (the final ablation plasma velocity far from the target) is comparable with the final shell velocity. Shorter-wavelength lasers improve the hydrodynamic efficiency because the energy is absorbed at higher plasma density and closer to the ablation surface. For 0.25- $\mu\text{m}$ -wavelength light incident upon reactor-sized spherical pellets, calculated hydrodynamic efficiencies are as high as 15 percent, or about three times the minimum efficiency needed for high-gain applications.

The distance between the driver energy-absorbing region and the ablation region is another important parameter affected by the heat transport. If nonuniformities in the energy absorbed are transmitted to the ablation surface, where the pressure is applied to the shell, the result will be an asymmetric implosion. Fortunately, such nonuniformities will tend to be smoothed out between the energy-absorption and ablation regions, provided this separation exceeds the wavelength of the disturbance. This smoothing mechanism, called the cloudy-day effect, has been found experimentally to be quite effective at a 1- $\mu\text{m}$  laser wavelength. However, for shorter-wavelength laser light, the very source of the improved absorption and greater hydrodynamic efficiency (higher-density absorption) aggravates the uniformity problem.

## SHELL ACCELERATION, UNIFORMITY, AND HYDRODYNAMIC INSTABILITIES

- Experimental results on ablatively accelerated pellet implosions have been encouraging, with respect to both implosion velocities and compression factors achieved, but the uniformity of the implosion is not yet adequate for compression to fusion densities. Various techniques for improving the implosion uniformity appear promising. Hydrodynamic instabilities, which would aggravate the problem, do not seem to be so severe as initially predicted.

Investigations of pellet-shell acceleration and hydrodynamic behavior have been accomplished by imploding actual pellets, using multiple-sided irradiation facilities, or by studying the acceleration of thin planar targets.

Early implosion experiments worked in the "exploding pusher" regime. In these experiments, small glass microballoons containing gaseous D-T were irradiated with intense short-duration light pulses. The laser-heated electrons deposited energy so quickly in the glass that the shell exploded. Roughly half of the exploding shell (pusher) traveled inward, first driving a shock wave through the D-T gas and then compressing the postshock material. Copious thermonuclear neutrons were generated as the D-T fuel heated to temperatures of many kiloelectron volts. However, the preheat levels of these targets, and the exploding pusher behavior, limited their peak fuel densities to a few times liquid density, far below the densities required for high-gain pellets.

Most present-day implosion work has advanced to the more relevant ablative mode. Ablation acceleration or implosion occurs as a result of the continuous acceleration of ablating material. These experiments either utilize thicker shells, to reduce hot electron preheat, or use lasers operating in a lower-irradiance or shorter-wavelength regime, where hot electrons are not dominant. This implosion mode is expected to scale successfully to large inertial-fusion devices.

Multinosecond 1- $\mu\text{m}$  lasers operating below  $10^{14}$  W/cm<sup>2</sup> have been used to produce well-behaved ablative accelerations. Planar targets have been ablatively accelerated to velocities of 160 km/s, with preheat below 10 eV and velocity uniformity to within 7 percent. Acceleration uniformities within 2.5 percent over almost a square millimeter have been achieved in other planar target experiments. Ablatively driven pellets have compressed D-T fuel to nearly a hundred times solid density, albeit with low temperature (about 400 eV). These experi-

ments are encouraging, but further progress is required to meet the critical-element physics requirements.

The pellet implosion must proceed with shell velocity nonuniformities below about 1 percent in order to compress the fuel properly. This requirement is aggravated by the fact that the pellet itself is susceptible to hydrodynamic instability at several phases during the implosion.

Driver nonuniformity problems can be alleviated in three ways. Use of hohlraum targets with conversion of driver energy to x rays provides a promising method of smoothing without requiring the beams of the driver to be symmetrically arranged. In the direct illumination approach, nonuniformities in absorption can be smoothed out by operating in a regime where the cloudy-day effect is operative. In fact, nonuniformity reductions of an order of magnitude have been demonstrated in 1- $\mu\text{m}$  laser light experiments. Finally, development of driver technologies that produce smoother beams should also be effective. All three methods are under active investigation.

A recent innovation in laser technology, called induced spatial incoherence, provides a promising method to reduce laser-beam nonuniformities to acceptable levels. The method works by dividing a broad-bandwidth laser beam into many smaller beamlets, with a small relative time delay introduced into each beamlet's path. If these time delays are longer than the beam coherence time, the laser nonuniformities will tend to cancel out statistically when the beamlets are overlapped on the target.

Hydrodynamic Rayleigh-Taylor instability can occur whenever a lighter fluid accelerates a heavy fluid. Inertial fusion analogs of the Rayleigh-Taylor instability occur when the low-density ablating plasma accelerates the dense shell, or later in the implosion when the dense shell decelerates on compressing the lighter fuel. Hydrodynamic instability causes two deleterious effects. First, the nonuniformities can prevent a central region of dense, hot D-T fuel from being created and cause the pellet to fail to ignite or even disassemble before full compression. Second, fuel can mix with the shell pusher material and spoil the ignition. There is an active growing theoretical program on the mechanisms, growth rates, and saturation levels for the Rayleigh-Taylor instability. A number of effects have been shown to reduce the growth rate below initial predictions.

Experiments are beginning to make significant headway into the study of the hydrodynamic stability of laser-accelerated targets. The evolution of accelerated "structured" targets, in which regular mass variations are introduced, has been followed using x-ray backlighting and double-target diagnostics. First indications suggest that the Ray-

leigh-Taylor instability growth rate may be less than classical, in agreement with the more recent theoretical predictions.

#### Prospects for Future Advances

- Two very large driver facilities are currently under construction in the United States: the NOVA neodymium-glass laser and the PBFA-II light-ion-beam accelerator. Construction of the world's most powerful CO<sub>2</sub> laser, ANTARES, was recently completed. These, and other smaller facilities, will be used to extend greatly our knowledge of the efficiency, symmetry, and stability of pellet implosions. In addition, heavy-ion-beam drivers have been proposed, and the search for efficient shorter-wavelength lasers continues.

As indicated in Table 4.12, a new generation of drivers is being developed. The NOVA neodymium-glass laser will have an output of 100 kJ of 1.05- $\mu$ m light (this will be frequency converted to shorter wavelengths, i.e., 0.53- and 0.35- $\mu$ m light); the ANTARES CO<sub>2</sub> laser has an output of 30 to 40 kJ of 10.6- $\mu$ m light; and the PBFA-II light-ion-beam accelerator will have an output of about 2 MJ of 4-MeV protons.

The new machines coming on line in the next few years will allow significant tests of key inertial-confinement fusion principles. For example, it is anticipated that the NOVA laser will be able to compress D-T fuel to about one thousand times liquid density, with fuel temperatures in the central hot spot in the 1-2 keV range. Such experiments will significantly test and extend our knowledge of the efficiency, symmetry, and stability of pellet implosion. The ANTARES CO<sub>2</sub> laser will test the suitability of long-wavelength laser light for inertial-confinement fusion. PBFA-II is anticipated to provide light-ion beams focused to sufficient intensity to test pellet implosions. The PHAROS, OMEGA, and CHROMA lasers will supplement the larger facilities by addressing important physics issues of inertial-confinement fusion.

Driver technology will continue to advance toward a high-energy, high-repetition-rate, efficient driver suitable for inertial-confinement fusion application. One promising system under development is the krypton-fluoride laser, with a wavelength at 0.26  $\mu$ m, which may satisfy the requirements for an efficient short-wavelength laser. Mega-joule-class glass-based lasers are also under evaluation; these systems could be frequency converted to provide short-wavelength light. Finally, particle-beam drivers, such as heavy-ion-beam systems and

light-ion accelerators, have the potential to offer high efficiency and repetition rates. Small, exploratory heavy-ion drivers are expected to operate in about 5 years.

Inertial confinement continues to be an active and exciting field. Research in the next decade will provide scientific and technical information needed to determine the physics of inertial-confinement fusion. In turn, this information will provide the basis for a decision in the late 1980s regarding the next generation of experimental facilities.

### ADVANCED FUSION APPLICATIONS

The discussion in this chapter has concentrated on the D-T fusion reactor, which would generate electricity by means of a conventional thermal conversion cycle, because the relatively large cross section of the D-T reaction makes it the easiest fusion process to achieve and apply. However, fusion processes offer a wide range of other possible applications, from production of fuel for light-water fission reactors to direct production of electricity using advanced fusion fuels. If achievable, advanced-fuel fusion reactors would produce almost no neutrons, thus reducing reactor activation by orders of magnitude, and would eliminate the need for tritium production.

One promising recent innovation has been the realization that fusion reaction rates can be altered significantly by polarizing the spins of the fuel nuclei. (The nuclei can be thought of as small magnetized gyroscopes.) At first sight, it might appear that the use of polarized nuclei for fusion could not possibly work, because the energy associated with polarization is approximately  $10^{-3}$  kelvin (K), compared with a plasma temperature of about  $10^8$  K. However, because of the very weak interaction between the particle motion and the spin, the use of this technique does indeed appear to be possible. By aligning the spins of D-T ions, the fusion reaction rate can be increased by a factor of 1.5. A more exciting application of spin-polarized fusion would be to reduce fusion neutron production, relative to electrically charged reaction products, by using certain combinations of polarized fuels. The simplest fusion reaction that produces no neutrons is the reaction between deuterium and helium-3; parallel polarization of the deuterons and the helium-3 ions can increase this reaction rate by a factor of 1.5 and at the same time substantially suppress the neutron-producing deuterium-deuterium reactions. (However, to make practical use of this reaction, a source of helium-3 must be found; although helium-3 does not occur naturally, it can, of course, be bred in a fission reactor.)



A fusion reactor could find many practical applications in addition to providing a heat source for conventional power generation. An example would be the use of radiation for chemical processing of synthetic fuels. Also, since the x rays and fast neutrons produced by a fusion plasma can pass through the walls of a reactor vessel and heat a blanket to almost any desired temperature, such reactors could find uses in high-temperature processing and in high-efficiency heat engines. Some attention has been given to the direct recovery of the energy of electrically charged fusion reaction products, but the possible applications of such fusion reactors have not yet been explored in any depth. For example, a compact mirror fusion reactor that produces most of its energy in charged particles could, in principle, make an ideal propulsion unit for large space missions.

The successful development of a fusion reactor could lead to the production of a wide variety of isotopes for scientific, industrial, and medical use, just as modern fission reactors do. Moreover, since the energetic particles produced in fusion reactions (alpha particles, protons, deuterons, tritons, as well as neutrons) are different from those produced in fission reactions, the range of possible isotope products should be much greater. Furthermore, the fluxes of energetic charged reaction products per unit surface area from a fusion reactor could be much larger than the flux of neutrons from a fission reactor.

The existence of a working fusion reactor should also provide a valuable stimulus to several branches of fundamental science. Certainly, a more profound understanding of plasma science itself will automatically result from the increased experience with hot, confined plasmas. In addition, fusion reactors should have a strongly beneficial impact on low-energy nuclear physics; specifically, they will provide the first large-scale terrestrial experience with stellar atomic processes. Another interesting aspect of fusion reactors is that they provide a totally new, unique type of energy source; in particular, they will produce copious microwaves and x rays, in addition to energetic particles. Just as neutrons from fission reactors have become powerful scientific tools, so should the versatile radiation from fusion reactors find numerous important scientific applications.

These are just a few of the possible advanced applications of fusion reactors. Perhaps the most exciting ultimate applications of fusion have not yet been conceived, as has been the case in most previous human ventures across new scientific and technological frontiers.

### FUNDING OF FUSION PLASMA RESEARCH IN THE UNITED STATES

Fusion plasma research in the United States is almost entirely funded by the federal government through the Department of Energy. (A very small fraction of fusion funding—not more than 3 percent of the total—is provided by the private sector and is mostly applied to nonmainstream magnetic-confinement approaches. In addition, the utility industry—through the Electric Power Research Institute—funds some fusion studies and small-scale developmental activities.)

Fusion approaches based on magnetic confinement are funded through the Department of Energy's Office of Energy Research, Office of Fusion Energy; inertial confinement is funded primarily through the Division of Military Applications, Office of Inertial Fusion, with some funding from the Office of Energy Research for the heavy-ion-beam approach.

The total appropriations for fusion research in each fiscal year since 1971 are shown in Figure 4.23. The appropriations are shown both in actual current dollars and, to remove the inflation element from funding growth, in equivalent constant 1984 dollars, using published official price indices. The appropriations for magnetic-confinement fusion are shown in Figure 4.23(a) and those for inertial-confinement fusion are shown in Figure 4.23(b). The tokamak program, and supporting technology, accounts for about 65 percent of the magnetic-confinement program. Within the total magnetic fusion program, activities that could be broadly categorized as relating to plasma research, i.e., including the construction of new experimental facilities but excluding engineering development and technology, account for about 75 percent of the total budget.

The 1970s was a period of rapid growth in the magnetic fusion program—prompted by early successes with tokamak confinement and sustained both by continued advances in tokamak parameters and by dramatic improvements in mirror concepts. The 1970s also saw the emergence of inertial confinement as a viable fusion-energy option. Figure 4.23 shows clearly that, when the inflation element is removed, fusion appropriations have leveled-off—indeed declined—in the late-1970s and early-1980s. If the momentum of fusion research is to be maintained—and, in particular, if the future advances in each of the confinement concepts described in the succeeding sections of this chapter are to be realized—appropriations must increase markedly in the late-1980s.

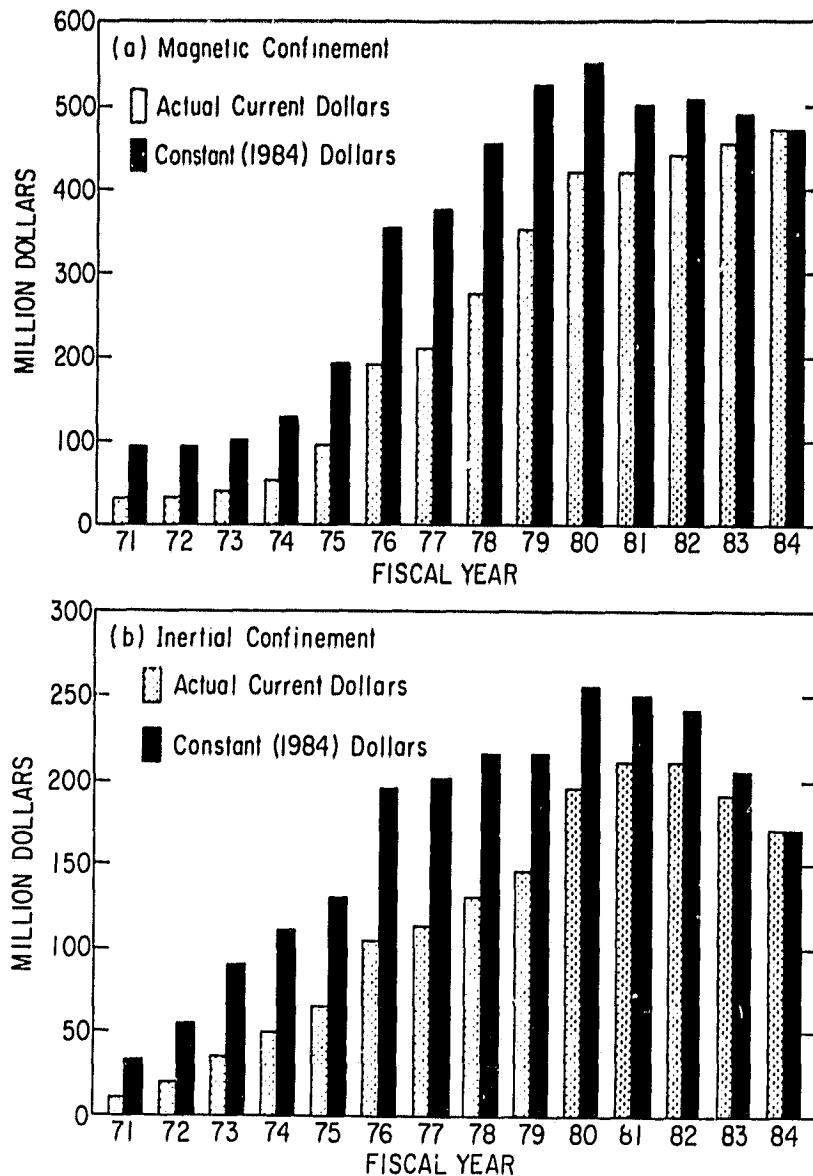


FIGURE 4.23 Federal appropriations for fusion research in actual and constant (1984) dollars. (a) Magnetic-confinement fusion. (b) Inertial-confinement fusion. Price indices obtained from Statistical Abstract of the United States, 103rd edition, page 452. Fiscal year 1976 contained 15 months. (Since the preparation of this chapter, the federal appropriation for magnetic-confinement fusion has decreased again—to \$440 million in fiscal year 1985.)

## PRINCIPAL FINDINGS AND RECOMMENDATIONS

### Magnetic Confinement

In all the main approaches to the magnetic confinement of fusion plasmas, the principal measures of plasma performance—plasma density, temperature, and confinement time—improved by more than an order of magnitude as a result of intensified fusion research in the 1970s. One approach—the tokamak—has already come within a modest factor of meeting the minimum plasma requirements for energy breakeven in D-T plasmas. These achievements have been made possible by rapid advances in plasma science.

The techniques used for plasma control and heating, the technology of high-power heating sources, and the precision of plasma measurements all improved dramatically during the past decade. There were equally rapid advances in plasma theory and numerical modeling, which are now able to explain much of the observed dynamical behavior of magnetically confined plasmas. The establishment of the National Magnetic Fusion Energy Computer Center (NMFECC) made possible many of these advances in theoretical modeling and data interpretation.

A particular strength of the U.S. fusion program is its broad base, which includes research on several alternatives to the mainline confinement concepts, to ensure that the maximum potential of fusion is realized.

A new generation of magnetic fusion facilities, coming into operation worldwide, will in the mid-1980s extend experimental plasma parameters to reactorlike values of density, temperature, and confinement time.

However, if the United States' pre-eminent position in the worldwide fusion program is to be maintained into the 1990s in the face of aggressive Japanese and European competition, the pace of new-device authorization that characterized the early 1970s must be restored soon.

The science of plasma confinement and heating has reached a stage of development that fully justifies the recent recommendations of the Magnetic Fusion Advisory Committee—an advisory committee to the Director of Energy Research, U.S. Department of Energy—which proposed a strategy for the development of magnetic confinement fusion with the following principal features:

- Initiation of a moderate-cost tokamak experimental facility (less

than \$1 billion plant and capital expenditures) designed to achieve ignition and long-pulse equilibrium burn;

- Depending on future assessments of the tandem-mirror data base, potential utilization of upgraded mirror facilities to test fusion blanket and engineering components;

- Vigorous pursuit of a broad-base program in magnetic-confinement research, encompassing tokamaks, mirrors, stellarators, bumpy tori, reversed-field pinches, and compact toroids.

A vigorous base research program is essential to technical progress in mainline tokamak and mirror research. Moderate-size experimental facilities are the primary sources of the scientific and technological innovations required to develop fusion to its fullest potential.

Continued research on alternate fusion concepts is essential to advance basic understanding of plasma confinement and to foster the development of approaches that show significant promise of improved reactor configurations.

Intensive research must continue on the theoretical and computational descriptions of magnetically confined plasmas and on supporting experiments in basic plasma physics. These have been a source of many promising new concepts in fusion research.

Continued strong university involvement will be essential to fusion research for the foreseeable future. Universities augment fusion research in the national laboratories in several unique and important ways. They educate and train professional fusion researchers; they provide the fusion program access to a breadth of talent and intellect in the sciences and engineering; and their research is a major source of innovative ideas and scientific and technological advances.

### **Inertial Confinement**

The United States has maintained world leadership in inertial-confinement fusion research since its inception in the late 1960s. Its near-term applications are military, with promising long-term applications to energy production. An inertial-confinement fusion reactor would have a relatively small containment volume, and its operation, maintenance, and repair may be relatively simple.

During the past decade, a vigorous international research effort was established to investigate the inertial-confinement approach to fusion. An impressive array of experimental facilities was developed, including neodymium-glass and  $\text{CC}_2$  lasers and light-ion accelerators, which led to considerable scientific progress. Investigations of laser-coupling

physics over a wide range of intensities and wavelengths showed that lasers with wavelengths of a micrometer and less have good coupling. D-T fuel was heated to thermonuclear temperatures in laser-irradiated implosions. Shells were ablatively accelerated to above  $10^7$  cm/s, with velocity nonuniformities of less than 5 percent. In implosions, final fuel densities of 100 times the liquid density of D-T were achieved with fuel temperatures of about 5 million degrees. These fuel densities are within a factor of 10 of the compression needed for a high-gain target.

On the basis of these findings, we recommend the following near-term emphasis and strategy for inertial-confinement fusion research:

- Use present driver facilities to determine the physics and scaling of energy transport and fluid and plasma instabilities to regimes characteristic of high-gain targets.
- Use the new generation of drivers under construction to implode D-T fuel mixtures to 1000 times liquid density required for high-gain targets and to implode scale models of high-gain targets to the density and temperature of the full-scale target.
- Identify and develop cost-effective, multimegajoule driver approaches.

Timely execution of this strategy will provide the basis for a decision in the late 1980s on the next generation of experimental facilities. Drivers in excess of a megajoule would allow demonstration of high-gain targets for both military and energy applications.

#### ACKNOWLEDGMENTS

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## Space and Astrophysical Plasmas

### PRINCIPAL CONCLUSIONS

1. The increasing precision of measurements, numerical modeling, and theory applied to space plasma problems amounts to a revolution in technique relative to 10 years ago. As a result, the study of space plasmas has become one of the primary motivations and experimental arenas for basic plasma research.

The solar system is the primary laboratory in which astrophysical plasma processes of great generality can be studied in situ.

2. Many practical systems, both civilian and defense, must operate in the highly variable and potentially hostile plasma environment of the Earth and solar system. Plasma processes in this environment also influence and even disrupt important ground-based systems over local and regional scales.

3. Because of the wealth of pertinent information flowing from solar-system plasma physics, and continuing advances in large-scale numerical modeling, magnetohydrodynamics and plasma physics are becoming central to the interpretation of many astronomical observations.

Studies of plasma behavior in extreme astrophysical environments, such as pulsars, enrich basic theory and may suggest future laboratory investigations and technology development.

4. Cosmic-ray observations provide important information about

space and astrophysical plasmas. The plasma physics of cosmic-ray acceleration and transport has made especially rapid progress in the past decade.

The improved precision of cosmic-ray-composition measurements now makes possible quantitative tests of theories of nucleosynthesis and galactic chemical evolution.

### PRINCIPAL RECOMMENDATIONS

To the federal agencies and advisory panels concerned with space and astrophysical plasma physics we make the following recommendations:

1. Observations, measurements, and experiments, in space and on the ground, are the key to productive research in space and astrophysical plasma physics.

We recommend implementation of the comprehensive research strategy outlined in *Solar-System Space Physics in the 1980's* (Space Science Board, 1980). These programs, and especially the International Solar-Terrestrial Physics Program and the Solar Optical Telescope, are the primary ones that will explicitly contribute to our knowledge of the physical processes in large-scale plasmas.

We endorse the programs proposed in *Astronomy and Astrophysics for the 1980's* (Astronomy Survey Committee, 1982) because they could make significant contributions to many problems in plasma astrophysics.

2. We recommend a national computational program dedicated to basic plasma physics, space physics, and astrophysics that will maintain the state of the art in the technology appropriate to large-scale theoretical models and simulations and provide access to users on the basis of peer review.

To the academic community

1. We recommend that plasma physics become a regular part of the university science curriculum in view of the increasing precision of its experimental and theoretical techniques, and in view of its many applications to space physics, astrophysics, and technology.



## RELATIONSHIP BETWEEN LABORATORY, SPACE, AND ASTROPHYSICAL PLASMA RESEARCH

### Definition of Space and Astrophysical Plasma Physics

Space and astrophysical plasma physics comprise many subjects with distinct historical origins. Space plasma physics includes solar and solar-wind physics, planetary ionospheric and magnetospheric physics, cometary physics, and the study of cosmic-ray acceleration and transport in the solar system. Solar research stands at the interface between space physics and astrophysics. The Sun's proximity makes it possible to make measurements, pertinent to the Sun's interior structure and to the plasma phenomena in its surface layers, that are obtainable for no other star. The subject of plasma astrophysics includes the generation of magnetic fields in planets, stars, and galaxies; the plasma phenomena occurring in stellar atmospheres, in the interstellar and intergalactic media, in neutron-star magnetospheres, in active radio galaxies, and in quasars; and the acceleration and transport of cosmic rays. Astrophysical questions motivate the study of relativistic plasmas. Each of these subjects depends on, and contributes to, laboratory plasma physics. Each has traditionally been pursued independently. Only recently has there been a tendency to view them as one unified discipline.

### Relationship Between Laboratory and Space Plasma Physics

The Study Committee on Space Plasma Physics (Space Science Board, 1978) expressed this relationship as follows:

Space and laboratory experiments are complementary. They explore different ranges of dimensionless physical parameters. Space plasma configurations usually contain a much larger number of gyroradii and Coulomb mean-free paths than is achieved in the laboratory plasma configurations. In the laboratory, special plasma configurations are set up intentionally, whereas space plasmas assume spontaneous forms that are recognized only as a result of many single-point measurements. Space plasmas are free of boundary effects; laboratory plasmas are not, and often suffer severely from surface contamination. Because of the differences in scale, probing a laboratory plasma disturbs it; diagnosing a space plasma usually does not. The pursuit of static equilibria is central to high-temperature laboratory plasma physics, whereas space physics is concerned with large-scale time-dependent flows. . . .

Certain problems are best studied in space. . . . Certain problems could be more conveniently addressed in the laboratory. . . . Theory should make the results of either laboratory or space experiments available for the benefit of the whole field of plasma physics.

The recent strengthening of theoretical space plasma physics, together with the increasing capability of space plasma instrumentation and the superiority of the space environment for certain types of measurements, means that the experimental diagnosis and theoretical interpretation of some space-plasma processes now matches in precision the best of current laboratory practice. This is especially true in the field of wave-particle interactions, where non-Maxwellian particle distributions, and the plasma waves they create, have been measured with such high resolution that theoretical instability models had to be increased significantly in precision.

#### **Relationship Between Space and Astrophysical Plasma Research**

The study of plasmas beyond the solar system has developed more slowly than space plasma physics for a fundamental reason: the microscopic plasma processes that regulate the behavior of astrophysical systems cannot be observed directly, as they can in space and in the laboratory. Now, however, the modern theoretical and computational techniques developed to understand laboratory and space measurements have opened the door to modeling of the plasmas in the still larger and more exotic environments of astrophysics, where observation suggests primarily the starting point in model development.

The interplay between small- and large-scale processes is characteristic of space and astrophysical plasmas. Magnetohydrodynamics (MHD) describes large-scale fluid systems and identifies, locates, and characterizes the small-scale plasma processes that regulate their global dynamics. In general, the MHD flow and the associated plasma processes must be modeled simultaneously to achieve complete and self-consistent understanding.

Many of the MHD systems studied in the solar system have important analogs in astrophysics. Space and astrophysical systems naturally involve similar plasma processes. We illustrate these remarks by discussing two types of MHD systems, winds and magnetospheres, and two plasma processes, particle acceleration and magnetic-field reconnection, that occur in them.

## MAGNETOHYDRODYNAMIC ATMOSPHERES AND WINDS

The outer layers of the Sun are a convective heat engine, whose motions produce both large- and small-scale magnetic fields. These magnetic fields do not spread uniformly over the solar surface, but instead concentrate into intense, small-scale flux tubes. The evolution of these surface magnetic fields occurs on time scales millions of times shorter than predicted by classical kinetic theory. The underlying processes—compressible convection, the interaction of turbulent conducting fluids with magnetic fields in a convecting atmosphere, magnetic buoyancy—are ubiquitous and yet poorly understood. Most of the planets have magnetic fields whose origins are due to dynamo action in their interiors; the vast majority of stars in our Galaxy are now believed to have magnetic fields much like the Sun's; and our Galaxy contains interstellar magnetic fields that are also believed to arise because of dynamo action.

The presence of magnetic fields in the Sun's outer layers has yet another consequence: the interaction between the surface magnetic fields and turbulent motions heats the solar corona. Although we do not yet know the precise mechanism responsible for the heating, we do know that most of the heated plasma is trapped by the solar magnetic fields and is observed to emit vigorously in the UV and in x rays; some of it, however, escapes into interplanetary space from open magnetic structures in the solar corona. This escaping hot gas is subsonic near the Sun but becomes supersonic as it flows outward to become the solar wind. This wind carries outward not only plasma and energy but also the embedded magnetic fields and angular momentum. Thus, the solar wind carries energy away from the solar corona and decreases the Sun's mass, magnetic flux, and angular momentum. The transport of angular momentum is sufficiently vigorous to account entirely for the Sun's loss of angular momentum since it reached the main sequence. The solar wind is finally decelerated to subsonic speeds when it encounters the interstellar medium. The solar-wind injects both nuclear-processed matter and magnetic fields into the interstellar medium.

Magnetized atmospheres and winds of the kind just described are exceedingly common. Plasma streams out into space from the planets' polar ionospheres in miniature versions of the solar wind—polar winds. The *Einstein* observatory has shown that stars with convecting outer layers have x-ray-emitting coronas, indicating surface magnetic activity and winds much like the Sun's; these stars constitute the vast majority of stars in our Galaxy. UV and x-ray observations have also shown that highly evolved stars with convecting outer layers do not

trap the heated plasma to form x-ray-emitting coronas, but rather eject the gas in the form of extremely massive winds. Indeed, much of the interstellar medium is filled with the blended wind material from these evolved stars and from supernova remnants. Because the densities, velocities, temperatures, and magnetic-field strengths in the interstellar medium are similar to those in the solar wind, many in situ observations of the interplanetary medium are automatically relevant to astrophysics. The interstellar plasma may also expand out of our Galaxy as a wind.

Winds that are confined by surrounding gas pressure take the form of collimated bipolar jets, which are observed to flow away from such diverse systems as stars in the early phases of formation, the exotic compact stellar system SS-433, and radio galaxies and quasars. Super-high-energy, relativistic plasma winds appear to flow away from pulsars and active galactic nuclei.

The solar and atmospheric winds are the only astrophysical fluids accessible to detailed diagnostics and in situ measurement. Since the solar wind in particular has been as completely diagnosed as any laboratory plasma, a detailed theoretical understanding of it is being developed.

#### PLANETARY AND ASTROPHYSICAL MAGNETOSPHERES

The Earth has an atmosphere above the one we breathe that is made of plasma—the magnetosphere. Beyond the magnetosphere, the plasma behavior is controlled by the solar wind. Within it, the Earth's magnetic field organizes the behavior of the plasma; it traps energetic particles to form radiation belts; and it transmits MHD stresses between the magnetosphere and atmosphere, a process that leads to auroras. The solar wind interacts with the magnetosphere to set the plasma inside in motion and to stretch the Earth's field into a long magnetic tail. Figure 5.1, a drawing of various regions of the magnetosphere alluded to above, does not convey how variable and dynamic this MHD system really is.

Each planetary body in the solar system has a distinctive magnetosphere, and we learn much by comparing their properties. A planet's size, rotation rate, magnetic field, satellites, and distance from the Sun influence the type of magnetosphere that it will have. Since the moon has no dynamo magnetic field, the solar wind interacts directly with its surface. The solar wind interacts with Venus' ionosphere. Mars may have a mixed magnetic and ionospheric interaction. Mercury has a magnetic field but no ionosphere. The Earth has a strong

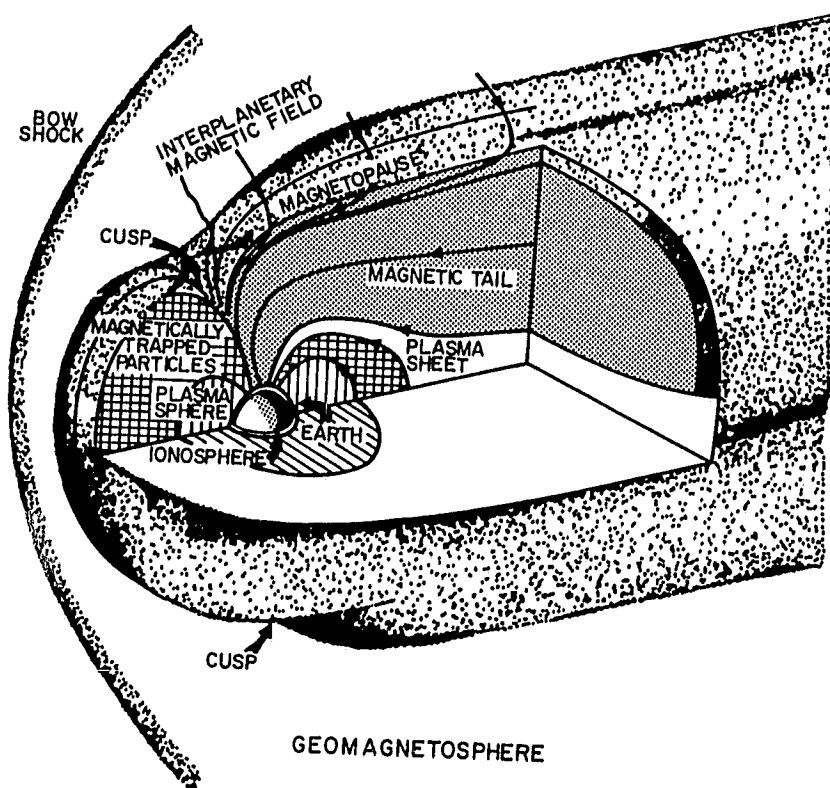


FIGURE 5.1 The Earth's magnetosphere. This imaginative drawing of the Earth's magnetosphere is a collective creation of the space research community, based on 25 years of measurements and theoretical modeling. It shows various features of the magnetosphere that will be discussed in this report. Standing ahead of the magnetosphere in the solar wind is a bow shock. The solar wind stretches the Earth's magnetic field into a long tail downstream. The northern and southern lobes of the tail are divided by a sheet of hot plasma. Impulsive plasma acceleration, probably due to reconnection, occurs in the tail and is probably related to violent disturbances in the pattern and strength of the auroras in the Earth's upper atmosphere and ionosphere. These disturbances are called substorms. The properties of the geomagnetically trapped energetic particles, the Earth's radiation belts, are determined by the balance of substorm acceleration and particle diffusion and transport. Such drawings cannot communicate the dynamism of this magnetohydrodynamic system.

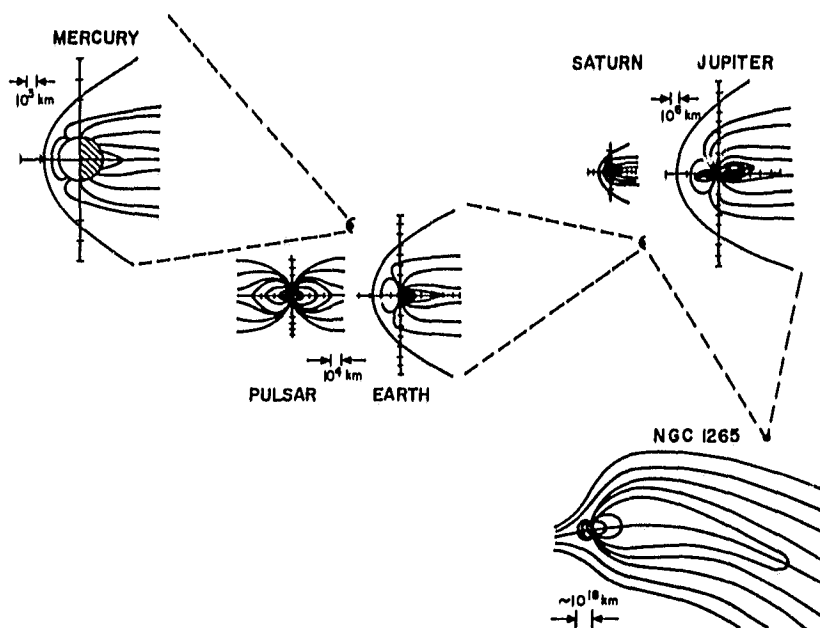


FIGURE 5.2 Planetary and astrophysical magnetospheres. This figure illustrates the enormous range of spatial scales to which the concepts of magnetospheric physics apply. Mercury's magnetosphere, the smallest in the solar system, has a size of a few thousand kilometers. It is about a factor of 10 smaller than the Earth's magnetosphere and pulsar magnetospheres. These, in turn, are about one hundredth the size of Jupiter's and Saturn's giant magnetospheres. All magnetospheres in the solar system are dwarfed by those of tailed radio galaxies, a trillion times larger than Jupiter's.

magnetosphere but it rotates slowly. Jupiter's rapidly rotating magnetic field couples with heavy-ion plasma from the satellite Io to form a binary magnetosphere. Saturn is an aligned rotator, whose spin and magnetic dipole axes are parallel. Recent ultraviolet observations indicate that Uranus has auroras, a strong indicator of magnetospheric processes; its magnetosphere may be pole-on to the solar wind, unlike all others known. Neptune's, if it exists, may be affected by interstellar neutral atoms. Finally, the solar wind interacts with neutral gases expanding from the nuclei of comets to form cometary magnetospheres.

Figure 5.2 sketches the magnetospheres of Mercury, Earth, Jupiter, and Saturn; they range in size from Mercury's ( $10^3$  km) to Jupiter's ( $10^6$  km), the largest MHD object in the solar system other than the solar wind itself. Figure 5.2 also shows two kinds of astrophysical

magnetospheres. Pulsars are rapidly rotating highly magnetized neutron stars that generate and expel highly relativistic plasmas from their magnetospheres. There are striking similarities between pulsar magnetospheres and Jupiter's magnetosphere, both in their rotationally driven flows and in their pulsed, periodic radio emissions. Pulsar magnetospheres are comparable with the Earth's in size. At the opposite extreme in size are the so-called "tailed radio galaxies." It has been proposed that their magnetic fields might have been stretched into a long tail by the moving galaxy's interaction with intergalactic plasma, in roughly the same way that the Earth's magnetic tail is created.

Our understanding of pulsars and tailed radio galaxies has certainly benefited from our awareness of analogous magnetospheric processes in the solar system. However, the parameters of space and astrophysical magnetospheres can differ so much that the day-to-day problems faced by researchers in these fields are quite different, and we observe them in very different ways. Nonetheless, the fact that both types of magnetosphere present similar questions about plasma dynamics gives us confidence that their physics is basically unified.

#### MAGNETIC-FIELD RECONNECTION

Suddenly the dark polar sky is pierced by a brilliant flash of light. Within minutes, a dazzling array of auroral forms stretches from horizon to horizon, million-ampere currents surge through the Earth's atmosphere and out into space, and 100 billion ( $10^{11}$ ) watts of power are dissipated in the Earth's atmosphere—a magnetospheric substorm has begun (Figure 5.3). On the Sun, a burst of x rays near a dark sunspot signals the beginning of a catastrophic disruption of the solar corona—a solar flare. Relativistic flare electrons heat the chromosphere to x-ray temperatures. A strong shock wave moves through the corona and begins a journey into interplanetary space that will carry it beyond all the planets of the solar system. The optical and x-ray luminosities start to build up in a distant quasar. Within a day, the quasar's luminosity will exceed the total power of a thousand galaxies. A sudden plasma loss occurs in a tokamak fusion device. These diverse phenomena seem unrelated. Nonetheless, they may share a common origin—the release of stored magnetic energy by the mixed MHD and plasma process of reconnection.

Violent reconnection can lead to spectacular events such as those above, but even in its more quiescent forms, reconnection can determine the behavior of MHD systems. Consider the interaction between



FIGURE 5.3 The aurora from the ground. An observer in the Earth's polar regions can often look upward at the fiery auroral displays 100 km above him in the upper atmosphere. Their colors, complex patterns, and violent motions have fascinated observers for centuries. It has been given to this generation of space plasma physicists to understand how the aurora is made. Turbulent plasma processes some 5000 km above the Earth accelerate a beam of electrons downward. When they hit the upper atmosphere, these electrons cause the molecules and atoms there to radiate. The auroral acceleration processes may be activated by violent events in the Earth's magnetic tail, caused by reconnection.

the magnetized solar wind and the Earth's magnetosphere. Reconnection between solar wind and originally closed magnetospheric field lines opens some Earth field lines to interplanetary space. Energetic particles that ordinarily would not hit the Earth can be guided along open field lines into the Earth's polar atmosphere. Thus, reconnection changes the topology of the Earth's magnetic field. More importantly, reconnection enables the solar wind to do work on the magnetosphere, to set the plasma inside in motion. The basic energetics of the magnetosphere are in large part determined by the rate of reconnection. Or consider the magnetic fields in the solar corona. It is thought that a balance is set by the creation of magnetic fields by turbulent convection below the solar surface and its destruction by reconnection



in microflares in the corona. Only when reconnection has been temporarily inhibited can the magnetic field increase enough to produce a spectacular flare by the reconnection that ultimately occurs.

In sum, the effects of reconnection must always be considered in MHD models of space and astrophysical systems. Not only can reconnection influence the quiescent magnetic configurations of such systems, but it can cause sudden, dynamic reconfigurations of their magnetic fields.

#### PARTICLE ACCELERATION AND COSMIC RAYS

An astonishingly large fraction of the energy in space and astrophysical plasmas is in the form of energetic particles. For example, cosmic rays comprise about one third of the total energy density of the interstellar medium.

The energetic particles themselves lead to important diagnostics of astrophysical systems. The observed cosmic-ray elemental and isotopic abundances are beginning to constrain models of nucleosynthesis and galactic evolution. We can infer the magnetic fields in many astrophysical systems by measuring the synchrotron radiation generated by electrons accelerated to relativistic energies, a first step in constructing global MHD models of such systems.

Analogous of cosmic acceleration processes are observed in solar-system plasmas. Energetic particles have been observed from probable reconnection events in the Earth's magnetic tail and from solar flares. The  $\sim 10$ -keV electrons responsible for the terrestrial aurora are accelerated at 1000-5000 km altitudes above the Earth in regions that carry strong magnetic-field-aligned currents and, contrary to MHD assumptions, have parallel electric fields. Intense radio emissions are generated in the auroral acceleration region. Auroras and radio emissions have also been observed at Jupiter and Saturn, and auroras at Uranus, indicating that such acceleration occurs at these planets.

Collisionless shock waves, either propagating in the solar wind or standing ahead of the planets, are observed to accelerate particles by processes similar to those now thought to generate cosmic rays. Shock waves of similar strength to those found in the interplanetary medium, propagating under similar conditions, and driven by supernova explosions are believed to be the primary source of galactic cosmic rays. Although it is not possible to detect the plasma processes responsible for particle acceleration in supernova shocks, theories of cosmic-ray acceleration can be tested by measurements of solar-system shocks together with measurements of galactic cosmic-ray energy spectra and

composition. On an even larger scale, collisionless shocks may be responsible for the acceleration of relativistic electrons in extragalactic radio sources.

### **The Unifying Physical Problems**

Laboratory, space, and astrophysical plasma research is unified by a shared set of physical problems of true intellectual significance. The Committee on Space Plasma Physics (Space Science Board, 1978) identified six of these:

1. Magnetic-field reconnection,
2. The interaction of turbulence with magnetic fields,
3. The behavior of large-scale plasma flows and their interactions with magnetic and gravitational fields,
4. The acceleration of energetic particles,
5. Particle confinement and transport, and
6. Collisionless shocks.

To the above six, we add two more:

7. Beam-plasma interactions and the generation of electromagnetic radiation and
8. Collective interactions between neutral gases and plasmas.

Problem 3 and aspects of problem 2 are concerned with large-scale MHD systems, and the others relate to microscopic plasma processes.

The fact that such problems emerge from a variety of contexts demonstrates their general significance and suggests that their solution will find further applicability in contexts that we cannot imagine today. The existence of such general problems provides a basis upon which a network of common interests, personal interactions, and ultimately a common discipline is being built.

### **SPACE AND ASTROPHYSICAL PLASMA PHYSICS IN THE PAST 10 YEARS**

To communicate succinctly the flavor of space and astrophysical plasma research, we highlight here some of the progress made over the last decade on the eight problems defined above. Because Problem 3 is concerned with large-scale plasma systems, discussing it first places all the other problems in context.

**Problem 3: The Behavior of Large-Scale Plasma Flows****PLANETARY MAGNETOSPHERES**

Mariner 10 discovered a small highly active magnetosphere at Mercury that is energized by the intense solar wind near the Sun.

The Pioneer-Venus Mission provided an impressive volume of information about the interaction of the solar wind with the Venusian ionosphere.

Pioneer 10 made the first in situ measurements in Jupiter's magnetosphere. Pioneers 10 and 11 established the enormous scale and variability of Jupiter's magnetosphere, and Pioneer 11 made the first traversal of Saturn's magnetosphere.

The Voyager 1 and 2 missions established that Jupiter's rotation powers a radial outflow of heavy-ion plasma injected by volcanic activity at the satellite Io. The Voyagers also found that Saturn's magnetic dipole and spin axes are aligned, a fact that challenges current theories of planetary-magnetic-field generation. Saturn's magnetosphere proved to have an important interaction with the dense atmosphere of the satellite Titan.

**DYNAMICS OF THE EARTH'S MAGNETOSPHERE**

Observations of intense plasma flows in the Earth's magnetic tail indicated that substorms are initiated by reconnection relatively near the Earth, which activates the aurora and expels hot plasma tailward.

Large-scale convection cells, perhaps stimulated by a viscous interaction with the solar wind, were discovered in the plasma sheet separating the two lobes of the Earth's magnetic tail.

The field-aligned current systems in the magnetic tail proved to be consistent with theory in the auroral acceleration region near the Earth. Strong MHD and plasma turbulence are associated with the currents in the tail.

**MAGNETOHYDRODYNAMIC STRUCTURES IN THE SUN'S ATMOSPHERE AND IN THE SOLAR WIND**

Skylab measurements revealed the important difference between open and closed solar-magnetic-field structures. Open magnetic regions—solar coronal holes—generate fast streams in the solar wind. Solar flares occur in closed magnetic structures—solar coronal loops.

The Solar Maximum Mission ACRIM experiment showed that magnetic-field structures on the surface of the Sun are related to variations in the Sun's optical luminosity.

The German/United States Helios Mission extended measurements of the solar wind within the orbit of Mercury, and Pioneer 11 extended them past the orbits of Neptune and Pluto.

The solar-wind magnetic field proved to reverse direction across a time-variable, warped neutral sheet, and strong, corotating shocks were found in the distant solar wind, thereby altering our picture of how galactic cosmic rays are modulated by the solar wind.

#### MAGNETOSPHERES OF NEUTRON STARS

Phase-resolved spectroscopy identified an x-ray line plausibly at the electron cyclotron frequency in two x-ray sources. If this identification continues to hold up, it will be the first proof that neutron stars can have super-strong magnetic fields, of the order of  $10^{12}$  gauss—a fundamental hypothesis of pulsar and galactic x-ray source theories.

Detection of pulsed gamma-ray lines from the Crab and Vela pulsars proved that they generate super-high-energy particles and qualitatively supported the theoretical suggestion that electron-positron pair plasmas are created in pulsar magnetospheres.

MHD theories of radial transport in accretion disks suggested that processes similar to those in the solar corona may occur in accretion disk coronas.

#### MAGNETOHYDRODYNAMIC JETS

Active galactic nuclei frequently produce pairs of high-speed jets that propagate in opposite directions through the surrounding galaxy and out into the intergalactic medium, where they create the two-component radio emission characteristic of radio galaxies. Very-long-baseline interferometric measurements proved that the jets, which were theoretically anticipated, are accurately aligned on the light-year scale of the nuclei and on the  $10^5$ - $10^6$  light-year scale of the double radio components (Figure 5.4). Some jets appear to expand faster than the speed of light, a kinematic effect that indicates that the flow speed can be relativistic.

Jets were also associated with galactic objects, such as the energetic system SS-433, or stars in the early stages of formation.

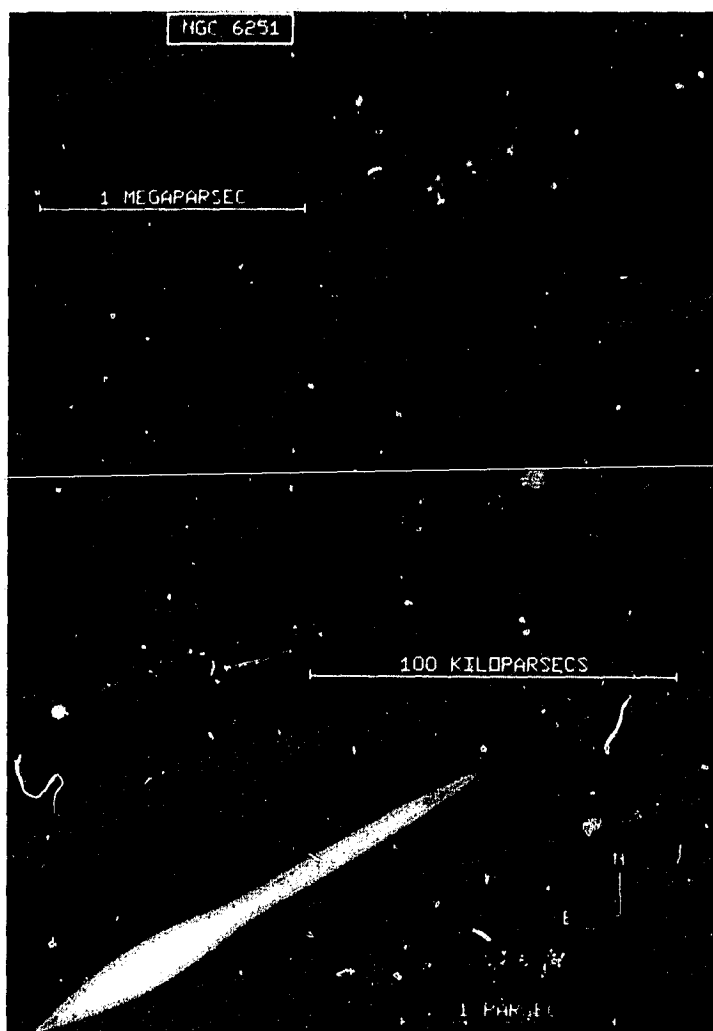


FIGURE 5.4 A galactic jet. This figure shows three computer-constructed radio images of the radio galaxy NGC 6251, taken by different observational techniques and superposed to show structure on three different scales. Color denotes radio intensity, with white the most intense. The twin lobe pattern of radio emissions from extragalactic radio sources has been familiar since the 1950s. These lobes have a scale of millions of parsecs, much larger than the parent galaxy. (1 parsec = 3.26 light-years.) A bridge of radio emission appears to connect the galaxy to the upper right-hand lobe in the top panel. Higher-resolution measurements (middle panel) reveal that this bridge is a highly collimated jet that connects directly to a bright source at the center of the galaxy. (The stellar light of the galaxy does not appear in this radio image.) The very-long-baseline-

## GENERAL RELATIVISTIC ELECTRODYNAMICS

It was suggested that the rotational energy of massive black holes, hypothesized to reside in the nuclei of active galaxies, may be extracted by electromagnetic torques. The plasma environments of these black holes would then be similar to pulsar magnetospheres.

**Problem 1: Reconnection**

Bursts of million-electron-volt particles associated with rapid plasma flows in the Earth's magnetic tail indicated that inductive electromotive forces are important to magnetospheric dynamics and suggested that tail reconnection is unsteady and perhaps explosive.

Rigorous analytical theory and numerical simulations established that a slow shock model proposed in 1964 is the correct description of reconnection in the MHD limit. The ISEE-3 spacecraft recently identified the slow shocks predicted by theory to exist in the geomagnetic tail.

Theoretical understanding of the collisionless tearing limit of reconnection was consolidated, and an explosive tearing instability was proposed analytically and simulated numerically.

A laboratory experiment diagnosed with high precision the turbulent transport processes occurring in a strong guide field plasma regime appropriate, perhaps, to solar-flare conditions.

**Problem 2: Interaction of Turbulence with Magnetic Fields**

The *Einstein* observatory discovery that most stars exhibit solarlike surface activity proved that plasma processes are central to the physics of stellar chromospheres and coronas. The correlation of stellar

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interferometry (VLBI) technique enables the central source to be resolved on a scale of fractions of parsecs, less than the mean distance between stars. (Bottom panel.) This central source is still not resolved on this scale, but an extremely intense jet that is almost perfectly aligned with the features in the middle and top panels emerges from it. It is thought that mass accretion onto a massive black hole at the center of the galaxy powers an MHD jet, which eventually deposits its energy into the radio lobes in the top panel. The radio emissions are generated by electrons accelerated to highly relativistic energies, which emit synchrotron radiation in the magnetic field of the jet. (We thank the California Institute of Technology and the University of Cambridge for permission to reproduce this photograph.)

activity with stellar rotation observed for solar-type stars will constrain theories of dynamo generation of stellar magnetic fields and the dissipation of these fields as they emerge through the stellar surface.

The solar-surface magnetic field proved to be concentrated in thin layers of strength of  $\sim 10^3$  gauss separated by larger regions of strength of  $< 10$  gauss. There is essentially no evidence for a smooth uniform field at the solar surface. These remarkable observations challenge theories of turbulent magnetohydrodynamic convection.

A coherent program of active and passive radar experiments, chemical releases, rocket measurements, analytic theory, and numerical simulations devoted to the equatorial ionosphere led to the most complete analysis of the nonlinear development of the Rayleigh-Taylor instability in plasma physics.

#### Problem 4: Acceleration of Energetic Particles

Measurements of the  $^{10}\text{Be}/^9\text{Be}$  ratio in galactic cosmic rays showed that their age—the time since they had been accelerated—is about 10 million years, thereby defining the efficiency required of any cosmic-ray acceleration mechanism.

Elemental and isotopic abundance measurements showed that cosmic rays are accelerated not out of material freshly synthesized in supernovae but out of interstellar material whose composition, while broadly similar to solar, is significantly different, very possibly owing to chemical evolution of the interstellar medium since the birth of the solar system.

The evidence that much of the volume of the interstellar medium is in a low-density plasma phase indicated that supernova shocks could propagate much further than originally thought. Together with the above cosmic-ray composition measurements, this revived the notion that supernova shocks Fermi-accelerate galactic cosmic rays out of the interstellar medium. The Fermi-acceleration particle energy spectrum was shown to be consistent with cosmic-ray observations.

The discovery of an anomalous component of low-energy cosmic rays that has an unusual elemental composition, rich in oxygen, nitrogen, and helium and is modulated by the solar-cycle-like galactic cosmic rays, suggested the existence of another source of cosmic rays, very likely in the outer reaches of the heliosphere.

Air-shower observations suggested that  $10^{14}$ - $10^{16}$  eV cosmic rays are richer in heavier elements than those at lower energies and that cosmic rays above  $10^{17}$  eV energies may be anisotropic, unlike cosmic rays of galactic origin.

Measurements of field-aligned currents, electrostatic and electromagnetic waves, and ion and electron distribution functions on auroral field lines were systematically assembled and combined with measurements of auroral light, ionization, motions, and structures, thereby setting the stage for comprehensive understanding of auroral acceleration.

Impulsive-particle-acceleration events, probably associated with reconnection, were found to accompany rapid reconfigurations of the Earth's magnetic tail.

Coordinated observations of energetic particles, x rays, and gamma rays from solar flares indicated that impulsive particle acceleration also occurs on the Sun.

It was found that processes within Jupiter's magnetosphere accelerate nearly all of the  $\sim 10$ -MeV electrons found in the heliosphere.

#### **Problem 5: Particle Confinement and Transport**

Detailed models of the magnetic-mirror confinement, radial diffusion, and turbulent pitch-angle scattering of energetic ions and electrons were created and successfully tested by observations in the magnetospheres of Earth and Jupiter.

Quantitative studies of the conduction of heat by electrons between the solar corona and chromosphere, which promise to make interpretation of chromospheric line emissions more secure, were initiated.

#### **Problem 6: Collisionless Shocks**

The strong dependence of the Earth's bow-shock structure on the parameters of the upstream solar wind was demonstrated by synopsis of individual detailed case studies, by the ISEE and other spacecraft.

A clear understanding of the discontinuous change in shock structure at the so-called first critical Mach number was achieved by a combination of spacecraft measurements, analytic theory, and numerical simulation.

Quasi-parallel shocks, which propagate nearly parallel to the upstream magnetic-field direction, proved to have extensive regions upstream that contain shock-accelerated particles and large-amplitude MHD turbulence, a property required by Fermi-acceleration theories.

Detailed measurements of the energetic particle distributions and plasma turbulence associated with interplanetary shocks and planetary bow shocks began to be used to test self-consistent shock-acceleration theories. These results are providing a solid basis for theories of the acceleration of cosmic rays by supernova shocks.



### **Problem 7: Beam-Plasma Interactions, and the Generation of Radio Emissions**

Jovian auroral radio emissions were measured directly from space for the first time. They extend a factor 10 lower in frequency than is possible to measure from the ground, and their characteristic frequency-time structure illuminates how they are modulated by the interaction between Jupiter's magnetosphere and its satellite Io.

Saturnian radio emissions were discovered and shown by the Voyager spacecraft to have a modulation entirely different from that of the Jupiter-Io system.

Detailed studies of the intensity, spectrum, and polarization of Earth's auroral kilometric radiation motivated substantial development of theory. The auroral electron beam may linearly excite the kilometric radiation directly, in which case the aurora resembles a giant gyrotron in space.

The magnetospheres of Earth, Jupiter, and Saturn confine a diffuse continuum of radio noise, whose lower cutoff frequency is the most sensitive indicator of the plasma number density. Detection of Jovian continuum radiation proved that Jupiter's magnetic tail extends to the orbit of Saturn and is the best vacuum so far encountered by man, with a density of  $10^{-5}$  particles per  $\text{cm}^3$ .

Detailed studies of the fine structure of continuum radiation illuminated how it is generated near the terrestrial plasmopause and magnetopause and by the interaction of Saturn's magnetosphere with its satellites.

A nonlinear theory of Type III radio emissions was created and supported by observation in the solar wind.

Detailed studies of pulsar radio emissions provided the most complete diagnosis to date of the microstructure of a highly relativistic plasma. Conclusive identification of orthogonal polarization states indicated that pulsar radio waves propagate in a magnetically birefringent medium similar to the ionosphere. The radio emissions of some pulsars were shown to consist entirely of discrete bursts, suggesting the action of nonlinear plasma processes.

### **Problem 8: Interactions Between Plasmas and Neutral Gases**

It was suggested in 1954 that a neutral gas would be rapidly ionized when its velocity through a plasma exceeds the so-called critical ionization velocity, given by equating an atom's kinetic energy to its ionization energy. Recent laboratory experiments together with the-

fields and dynamics, solar flares, and coronal heating, thereby creating the basis for general understanding of stellar activity.

The growing ability to make series of detailed high-resolution observations in many wavelength bands will render many astrophysical objects increasingly subject to theoretical models that explicitly take plasma processes into account.

Understanding of many space plasma processes will be sufficiently quantitative to make them reliable components of models of large-scale space and astrophysical systems. In addition to radiation-belt dynamics, the list of generally understood space plasma processes may include auroral acceleration, reconnection, collisionless shocks, and neutral-gas plasma interactions.

The first generation of large-scale numerical models of space and astrophysical systems will have been completed. Foreseeable advances in computing technology will lead to the creation of such models virtually simultaneously through space physics and astrophysics. The models will probably have made plasma physics central to the interpretation of many astronomical observations and have motivated new and different kinds of observations. One member of this class of models will have been tested by direct in situ measurements of the terrestrial magnetosphere's global dynamics, provided by the International Solar-Terrestrial Physics Program.

### **IMPACT OF RESEARCH ON SPACE AND ASTROPHYSICAL PLASMAS**

Research in this century has revealed a chain of interactions, almost all of which involve plasma physics, that connects activity at the surface of the Sun to the solar wind, and then on to the magnetosphere and atmosphere. The most spectacular manifestation of this solar-terrestrial interaction chain is the magnetic storm. The first evidence that a large solar flare might occur is the appearance of a complex sunspot group in the Sun's photosphere. Prompt electromagnetic radiation arrives at Earth a few minutes after the energy in the coronal magnetic fields associated with the sunspot group is suddenly released. Energetic solar-flare protons are guided by the solar wind and magnetospheric magnetic field into the polar atmosphere soon afterward. The enhanced ionospheric plasma produced by the energetic protons attenuates the radio noise received from cosmic radio sources. A day or so later, a shock wave passes over Earth, enveloping it in dense, hot solar-flare plasma that compresses the magnetosphere. Substorms increase in frequency and strength and inject hot plasma

into the Earth's inner magnetosphere to form a ring current, which creates the geomagnetic field depression and activity that first motivated the name magnetic storm. The auroras intensify and move to unusually low latitudes, creating a dense highly disturbed ionospheric plasma that interferes with radio communication and on occasion blacks it out altogether. Intense wind systems, sometimes of a world-wide scale, are generated in the upper atmosphere.

In its report *Solar-Terrestrial Research for the 1980's*, the Committee on Solar-Terrestrial Research (1981) has identified four areas where research on the solar-terrestrial interaction chain can clarify important impacts on society and technology:

1. Predictions about the space environment;
2. Effects on stratospheric ozone, which shields the life at the Earth's surface from the harmful effects of solar ultraviolet radiation;
3. Effects on ionospheric physics and radio propagation; and
4. Elucidation of potential connection between solar variability, weather, and climate.

Although items 2 and 4 have significant long-term implications, item 1 is at present the most important. Many practical systems, both civilian and defense, and all of our manned space endeavors, must operate in the highly variable and potentially hostile plasma environment of the Earth and solar system. Plasma processes in this environment also influence and even disrupt important ground-based systems over local and regional scales. Ground-based high-frequency communication systems in the auroral regions can be blacked out by magnetic storms. Entire aircraft have been electronically disabled by violent electrical discharges that occur when hot ring-current plasma envelops the spacecraft. The risk of such disasters can be reduced only by continuing attention to the effects of the plasma environment on spacecraft systems. It is clear that to work in the space environment, we must understand it.

Research on the solar-terrestrial interaction chain is the only way to learn how to predict the space environment. Because of the need to understand and predict its impact on military systems, the Air Force and Navy maintain significant research and monitoring programs in solar and solar-terrestrial physics.

One of the most important by-products of today's research on solar-system plasmas will be a generation of students and practitioners familiar with the space environment whose work will enrich tomorrow's space science and technology.

The Astronomy Survey Committee (1982) has characterized the motivations for astronomical research as follows:

Astronomy . . . is sustained by two of the most fundamental traits of human nature: the need to explore and the need to understand. Through the interplay of discovery, the aim of exploration, and analysis, the key to understanding, answers to questions about the Universe have been sought since the earliest times, for astronomy is the oldest of the sciences. Yet it has never been, since its beginnings, more vigorous or exciting than it is today.

Our own branch of astronomy, astrophysical plasma physics, is driven by the need to understand the unusual plasmas surrounding some of the most exotic objects brought to light by recent astronomical research. Our imaginations are challenged, and we are forced to extend plasma physics to comprehend them. The enrichment of plasma physics, the most important by-product of astrophysical plasma research, strengthens the technological potential of the entire field.

#### THE ROLE OF SPACE AND GROUND-BASED MEASUREMENTS AND OBSERVATIONS

The basis of space and astrophysical plasma physics is large: federally funded programs that support measurements and observations made from space and the ground. These programs have been studied extensively in previous reports sponsored by the National Research Council.

#### Solar-System Plasma Physics

*Solar-System Space Physics in the 1980's*, by the Committee on Solar and Space Physics (CSSP) of the Space Science Board (1980), gives a comprehensive strategy for experimental research in solar-system physics, nearly all of whose recommendations bear directly on solar-system plasma physics. Among other things, it proposes a four-spacecraft investigation of the transport of energy and plasma in the Earth's magnetosphere (the OPEN mission), high-resolution observations of solar surface phenomena (the Solar Optical Telescope), a solar probe, and active plasma experiments performed from the Space Shuttle. The internationalization of the OPEN mission, now called the International Solar-Terrestrial Physics Program, adds an important possibility that more spacecraft will join the effort to understand the magnetosphere's global dynamics.

Smaller-scale Explorer-class space missions were addressed in a subsequent CSSP report, *A Strategy for the Explorer Program in Solar and Space Physics* (Space Science Board, 1984). There it is recommended that "The size, complexity, and management of future Ex-

plorer missions should return to the original perceived philosophy of the Explorer program, i.e., relatively small, simple satellites." Furthermore, the CSSP found that the scientific opportunities in solar and space physics research merit an average of approximately one Explorer satellite opportunity a year.

*We recommend implementation of these two CSSP strategies because the programs that they recommend are the primary ones that will explicitly contribute to our knowledge of the physical processes in large-scale plasmas.*

The Geophysics Research Board in *Solar-Terrestrial Research for the 1980's* (Committee on Solar-Terrestrial Research, 1981) and in *National Solar-Terrestrial Research Program* (Committee on Solar-Terrestrial Research, 1984) recommends a program of ground-based measurements, designed to supplement the CSSP strategies, that will provide important information about the chain of physical interactions that links solar activity to changes in the Earth's magnetosphere, ionosphere, and atmosphere. We support the objectives of these reports.

Finally, planetary research makes an important contribution to solar-system plasma physics.

*Because the planets and comets provide different tests of magnetospheric physics, it is essential that experimental and theoretical plasma investigations continue to be an integral part of each planetary and cometary mission.*

### **Astrophysical Plasma Physics**

*Astronomy and Astrophysics in the 1980's*, by the Astronomy Survey Committee (1982), proposed four major and seven moderate new programs designed to benefit all of astronomy and astrophysics. We have examined each of the proposed programs and find that the majority will contribute to the observational basis of astrophysical plasma physics.

We now discuss four examples from the diversity of measurements that can contribute to research on astrophysical plasmas. The Advanced Solar Observatory, whose central element will be the Solar Optical Telescope, will make high-resolution measurements of plasma structures on the surface of the Sun. The Advanced X-Ray Astrophysics Facility (AXAF) will diagnose the high-temperature plasmas surrounding stars, black holes, neutron stars, and active galactic nuclei, in supernova remnants, and in numerous other objects. The Very-Long-Baseline Array of radio telescopes will make exceedingly high-resolution measurements of the spatial structure of objects, such as

galactic nuclei, in which electrons are accelerated to high energies. The moderate-scale programs to measure cosmic rays proposed by the Astronomy Survey Committee will provide direct evidence about how and where cosmic rays are accelerated, about the propagation of cosmic rays in the Galaxy, and about galactic evolution.

*We endorse the programs proposed in Astronomy and Astrophysics for the 1980's because, in advancing the entire field of astronomy, they will make significant contributions to many problems in plasma astrophysics.*

*Given implementation of these recommendations, the single most important step toward strengthening the role of plasma physics in the interpretation of astronomical observations will be to encourage theoretical and numerical models of large-scale plasma systems.*

#### **In Situ Measurements near the Sun**

Several years ago, the National Aeronautics and Space Administration (NASA) formed a project team, which, together with an external Science Working Group, studied a mission to the Sun called Starprobe. Starprobe would be an instrumented spacecraft designed to operate in the solar corona as close as 4 solar radii from the Sun's center. Starprobe would provide, for the first time, *local* sampling of the plasma, magnetic field, energetic particles, and turbulence in a stellar atmosphere. It would delineate the properties of the transition region where the subsonic coronal flow is converted into the supersonic and super-Alfvénic solar wind. The imaging available from close range would provide high-resolution information about solar surface features. It is possible to instrument the spacecraft to yield crucial information of the mass distribution in the solar interior, of importance to theories of stellar structure and gravitation. The final report of the Starprobe Science Working Group was never presented for further evaluation to the Space Science Board or to NASA's Space and Earth Science Advisory Committee.

From the joint perspective of solar system and astrophysical plasma physics, in situ measurements of a stellar corona could be as significant as the discoveries of the solar wind or the Earth's magnetosphere. For this reason:

*We recommend that NASA ask its advisory committees to evaluate a mission to the Sun.*

### Concluding Remarks

The brevity of our discussions of space and ground-based measurements and observations reflects only the extent to which these issues have been carefully discussed elsewhere. The large and complete studies that we referred to above are but one indication of the conviction shared by all researchers that measurements and observations are a *sine qua non* of science. To maintain U.S. leadership in space and astrophysical research, a vigorous program of space and ground-based measurements is absolutely essential.

### THE ROLES OF LABORATORY AND ACTIVE SPACE EXPERIMENTS

#### Laboratory Experiments

Many experiments help to develop basic theory, and so contribute indirectly to space and astrophysical research. A few have been designed specifically to elucidate processes occurring in space and astrophysical plasmas. Such experiments usually cannot reproduce the large ratios of system scale to basic microscopic scale lengths characteristic of natural plasmas, but if the relative ordering of the various dimensionless plasma parameters is similar to that in the system of interest, the laboratory results can be extrapolated satisfactorily.

Laboratory experiments and numerical simulations have similar advantages and limitations. The continuing refinement of detector technology and the great increase in precision and volume of data analysis made possible by the use of dedicated minicomputers now enable laboratory experiments to be diagnosed as thoroughly as a numerical simulation. Although an advanced computer can simulate many problems, and an experiment only one, experiments can be the method of choice for certain plasma problems and complement simulations for others. In these cases, experiments can give information as detailed as a simulation about real plasmas, rather than about mathematically idealized ones.

Laboratory experiments have been particularly important in confirming the existence of processes thought to occur in space plasmas. A *terrella* experiment, in which the flow of plasma past a magnetic dipole simulated the interaction of the solar wind with the Earth's magnetosphere, demonstrated the existence of the long postulated reconnection regions at the nose and tail of the magnetosphere several years before three-dimensional numerical simulations could do so.

Reconnection experiments in simple space-physics geometries, as well as in tokamaks, revealed the dynamic-magnetic-field reconfiguration and plasma acceleration generally expected by theory. Laboratory experiments first suggested, and later confirmed, the existence of electrical double layers and anomalous resistivity, which are involved in auroral particle acceleration. Laboratory experiments demonstrated how plasmas moving through a neutral background at the so-called critical ionization velocity suddenly bring the neutrals to full ionization and produce substantial momentum coupling.

*Past experience indicates that laboratory experiments will continue to contribute to space and astrophysical plasma physics.* Examples of areas where experiments are needed include the following. Efforts to clarify the microstructure and the collective wave-particle interactions occurring in the reconnection process are under way for a limited set of laboratory parameters. Studies of reconnection in a range of different plasma conditions are needed. It has been 10 years since the last laboratory collisionless shock experiment. Studies of high-Mach-number shocks would provide information, important to astrophysics, about shocks stronger than those typically found in the solar system. The processes limiting strong heat conduction merit continued laboratory study. Strong heat conduction takes place between the solar corona and chromosphere, the Earth's magnetosphere and ionosphere, the hot interstellar medium and cool interstellar clouds, and the surfaces and interiors of laser-fusion plasmas. Experiments on the interactions between relativistic electron beams and plasmas illuminate the physics of relativistic astrophysical objects such as pulsars. And, of course, the most important experiment of the next 10 years might well be one that finds an unforeseen new effect.

### Active Space Experiments

Here we discuss some experiments performed on space plasmas.

Very-high-frequency radar backscatter has been used for the past 20 years to diagnose both the large-scale properties and the small-scale plasma turbulence in the equatorial and auroral ionosphere. The nonlinear response of the ionosphere to intense high-frequency irradiation from ground-based radars has been studied at mid-latitudes for the past 10 years and more recently at auroral latitudes. Entirely analogous experiments have been performed on laboratory plasmas.

Chemical releases in the ionosphere have clarified the interaction between flowing plasmas, magnetic and electric fields, and neutral gases. They also confirmed the existence of parallel electric fields in the



auroral acceleration region. The United States/German AMPTE spacecraft mission is using chemical releases to provide similar information about conditions deep in the Earth's magnetosphere.

Electron beams injected from rockets into the ionosphere have been used to study the radiation from space plasmas as well as to diagnose the properties of the geomagnetic field.

The Space Shuttle is beginning to make possible large experiments, including chemical, beam, and wave injections, that will greatly increase the scope of active space experimentation.

*In sum, the past decade has seen the rapid growth of a new space-science discipline—plasma physics in space—in which experience gained in the laboratory and the talents of laboratory experimentalists have been used to advantage.*

The implications of this development are obvious. We have begun the long effort that may eventually result in a measure of useful control over our space environment. For this reason, we expect the already rapid growth to accelerate.

### THE ROLE OF THEORY

The creative interplay between theory and experiment is the scientific method, and the quantitative prediction and understanding of experiment and observation is the central function of theory.

Theory and theoreticians play another important role in our subjects. They express the unity in the diversity of plasma phenomena in the laboratory, in the solar system, and in the universe at large. They communicate conclusions, ideas, analogies, and techniques across disciplinary boundaries. Theoreticians have led the effort to unify space and astrophysical plasma physics.

### Space Plasma Theory

The Study Committee on Space Plasma Physics (Space Science Board, 1978) spoke firmly about the role of theory in solar-system plasma research:

The theoretical component of the space-plasma-physics effort needs to be strengthened by increased support and, most particularly, by encouraging theory to play a central role in the planned development of the field.

The Committee on Solar and Space Physics of the Space Science Board (1980) echoed the above recommendation in forceful terms:

Theory has to play an increasingly central role in the planned development of solar-system space physics. Moreover, theory and quantitative modeling should guide its entire information chain—data acquisition, reduction, dissemination, correlation, storage, and retrieval—to a higher level of sophistication, to provide prompt availability of coordinated data of diverse origins.

NASA's Solar-Terrestrial Theory Program, initiated in view of the above recommendations, has been one reason why solar-system plasma research has reached a new level of precision, whereby it now makes strong contributions to both general plasma physics and to the interpretation of space data.

*We heartily recommend continuance of the excellent support that space plasma theory has received in the past 5 years and, especially, of the Solar-Terrestrial Theory Program.*

#### **Theoretical Astrophysics**

The Astronomy Survey Committee (1982) recommended as a *pre-requisite* for new research initiatives:

[augmentation of] theory and data analysis, to facilitate the rapid analysis and understanding of observational data; . . .

The Astronomy Survey Committee recommended a program like the Solar-Terrestrial Theory Program for theoretical astrophysics. The Theory Study Panel of the Space Science Board (1983) made a similar recommendation:

*We recommend that NASA establish independent theoretical research programs in planetary sciences and astrophysics, with objectives similar to those of the solar-system plasma-physics theory program.*

Experience suggests that such a theory program could be highly successful and, in particular, that it might transform plasma astrophysics.

*Theory and numerical modeling must both be strengthened in order that plasma physics play the central role in the interpretation of astronomical observations warranted by the fact that most of the universe is in the plasma state.*

## THE ROLE OF NUMERICAL MODELS AND SIMULATIONS

### Why Quantitative Models Are Essential

We must picture the entire magnetosphere of the Earth before we can deduce where and how its plasma processes operate, yet we must understand what the processes do before we can determine the structure and dynamics of the magnetosphere. This essential difficulty is repeated through space and astrophysical plasma physics: plasma processes both determine, and are determined by, their parent system's global MHD configuration.

Twenty years ago, imaginative drawings—cartoons—guided space plasma research. Despite their naiveté, they were important. Even then, fairly detailed information about the local behavior of plasmas in the magnetosphere was being acquired. The significance of this information was evaluated with the help of drawings, which provided a conceptual link between local measurements taken at different points in space and time. As our picture of the magnetosphere grew more complete, so also did our grasp of the plasma processes regulating its behavior. Until this finally occurred, many scientific controversies would have been settled had it been possible to photograph the magnetosphere.

We *can* photograph astrophysical systems. However, our photographs detect photons that are usually generated by mechanisms indirectly related to the MHD and plasma processes that regulate the structure and energetics of the systems under study. We have no in situ measurements, as we do in the solar system, to tell us even the most basic plasma parameters. These must be inferred using our knowledge about how the light we observe was generated. Our photographs provide only a two-dimensional picture at one instant of time of three-dimensional, evolving systems. Thus, we study classes of related objects of different ages to deduce how they evolve in time, and we use drawings to elucidate the relationships between their structure, dynamics, evolution, and the radiation that we measure.

To achieve quantitative agreement between theory and observation, it is essential to progress beyond the cartoon approximation to quantitative models. It is less obvious, but no less true, that the process of model building is also a process of discovery. By constructing a series of models we are led to appreciate the relationships between the parts and the whole of the time-variable, three-dimensional systems that we observe and to perceive how microscopic processes regulate their

structure and behavior. Models also suggest new measurements that then clarify the physics underlying the models.

In the past decade, our studies of solar-system plasmas have achieved a measure of quantitative understanding through the systematic use of analytic and, more recently, numerical models. The first generation of numerical models of astrophysical plasma systems is being created at this time. Because we cannot detect the underlying astrophysical plasma processes directly, we believe that the best strategy will be to create numerical models at the system level that postulate plasma and radiation processes and iterate between the system and process levels until quantitative agreement with observation is achieved. It is our perception that the present level of development of numerical technology, theory, and observations gives such a strategy a significant chance of success for the first time.

The increasing urgency of the need for advanced numerical simulations and models may be perceived from the phrasing of successive recommendations of National Research Council and NASA panels.

The *Report on Space Science 1975* by the Space Science Board (1976) simply noted for all the space sciences that

Results from . . . theoretical modeling have been of critical importance in planning and supporting space missions.

without commenting on the needed computational facilities.

The Advocacy Panels in their unified recommendations to the Study on Space Plasma Physics (Space Science Board, 1978) recommended the following:

Strengthening theoretical solar-system plasma physics and, to aid in achieving this goal, support for computer modeling. . . .

The International Magnetospheric Study Working Conference on Magnetospheric Theory made the following explicit recommendation for this field (Committee on Solar-Terrestrial Research, 1979):

Future theoretical progress must involve the use of plasma simulation and large-scale numerical modeling of magnetospheric dynamics in parallel with the development of pure theory.

The Committee on Solar and Space Physics of the Space Science Board, in *Solar System Space Physics in the 1980's* (NAS, 1980), made a much more general recommendation:

. . . theory and quantitative modeling should guide [the] entire information chain [of solar-system plasma physics] to a higher level of sophistication. . . .

Recent recommendations for advanced computations for the broad field of astrophysics have been directed toward the computing facilities that will be needed. In *A Strategy for Space Astronomy and Astrophysics for the 1980's*, the Committee on Space Astronomy and Astrophysics of the Space Science Board (1979), among other recommendations for theory, advocated that:

NASA should make available time on its largest computers for theoretical problems of great complexity, which are often beyond the capacity of university-scale computers.

By 1982, the Astronomy Survey Committee felt it necessary to recommend, as a *prerequisite* for new research initiatives in astronomy:

Computational facilities, to promote data reduction, image processing, and theoretical calculations.

The Initial Report of the NASA/University Relations Study Group (NASA, 1983) recommended that NASA should provide to researchers in fields sponsored by NASA, including space plasma physics and astrophysics:

Major facilities [such as] . . . large, fast computer facilities of the Cray class, which would be used by several investigators and jointly by investigators at several institutions.

The above recommendations reflect the increasingly widespread perception that theory, just as experiment, depends crucially on technology.

### **System Models and Process Simulations in the Next Decade**

Realistic MHD system models will include the effects of collective plasma processes as regulating subelements; these processes can be individually simulated in idealized form. System models are conceptualized and executed at the fluid level, process simulations at the microscopic, kinetic level. Here we present examples of global models and local simulations that will be needed in the next 10 years.

### **SYSTEM MODELS**

An entire space project, the International Solar-Terrestrial Physics Program (ISTP), has been designed and recommended with the idea

that an MHD magnetospheric model with realistic microscopic elements will also be created and tested by the data. The multiple spacecraft and ground facilities associated with the ISTP will measure key parameters pertinent to the MHD model, together with the local plasma processes that regulate the dynamics of the magnetosphere.

The ISTP project will provide the first systematic experimental test of a comprehensive magnetohydrodynamic model of a large-scale flowing system. Testing the model will force the development of innovative methods of data analysis and dissemination.

The ISTP magnetospheric model will be the first MHD system model in space physics and astrophysics to include all known, pertinent plasma process elements.

The ISTP magnetospheric model will be a prototype of what must be done if hydrodynamic and MHD models are to play their potentially powerful role in the interpretation of remote astronomical observations. Solar-terrestrial models that successfully meet the test of detailed measurements at both large- and small-scale processes would substantially increase our confidence in models of more distant astrophysical systems.

The first large-scale astrophysical plasma models are being created for solar physics, as hydrodynamic models of the turbulent convection zones of the Sun and similar stars have been extended to include MHD. These models will allow us to test our understanding of fluid-magnetic field interactions as the data from the next generation of high-resolution solar instruments become available. (The first and most important of these is the Solar Optical Telescope.) System models will be crucial to the interpretation of these anticipated high-resolution data because of the intimate connection between the processes that determine morphology and those that produce the photons that we observe.

System models analogous to those just described are being developed for accretion disks near neutron stars and black holes and are being used to interpret data from galactic x-ray sources and active galactic nuclei. Similarly, the first generation of models of bipolar jets is currently being constructed.

#### PROCESS SIMULATIONS

Twenty years of experience in fusion plasma physics, and 10 years in space plasma physics, indicate that numerical simulations are one of the best ways to gain insight about nonlinear plasma processes. For example, simulations have illuminated how  $H^+$  and  $O^+$  ions are accelerated by auroral plasma turbulence and then ejected into space.

The output of such microscopic plasma calculations must be fed back into system models. In the above example, the  $H^+$  and  $O^+$  ions add mass to, and decelerate, the MHD flow in the magnetosphere.

Advanced numerical simulations will be very important to reconnection, where three-dimensional kinetic simulations in a time-dependent magnetically complex configuration are required to resolve our outstanding theoretical questions. Such problems as wave-particle interactions, generation of radiation in plasmas, collisionless shock structure, strong heat conduction, and many more will continue to benefit from advanced numerical simulations.

Another application of detailed modeling is to plasmas with super-high-energy densities. For example, the ultra-high plasma temperatures believed to prevail at the centers of quasars and active galaxies are far more extreme than those encountered either in the laboratory or the solar system and probably lead to some fascinating phenomena associated with the creation of electrons and positrons from heat energy. The electron-positron recombination line has been detected from the nucleus of our Galaxy, suggesting the existence of relativistic plasma processes there. The superstrong magnetic fields in neutron stars can lead to an unusual pair-production process that is thought to populate pulsar magnetospheres with positronic plasma. Detailed models of these processes can be checked by x- and gamma-ray observations of pulsars. From the meager theoretical work to date, it is already clear that an understanding of such plasmas, and the complex role played by electron-positron pairs, will provide novel theoretical constraints on the sizes, luminosities, and temperatures of some of the most energetic astrophysical objects.

#### OVERALL CONCLUSIONS

Our review of the models and simulations needed in the next 10 years has led us to the following conclusions:

1. Many problems in space and astrophysical plasma physics have evolved to the point where numerical system modeling is a next logical step. These problems include planetary magnetospheric structure, solar convection and coronal structure, three-dimensional structure of the solar wind, supernova remnants, astrophysical jets, pulsar magnetospheres, and accretion onto neutron stars and black holes.

2. Many microscopic plasma problems that arise in the study of space and astrophysical systems would benefit by coordinated simulation efforts.

### **Proposal for a Dedicated, Advanced Computational Program**

Plasma physics was a pioneer in the successful utilization of large-scale computations, for fluid, MHD, hybrid, and kinetic models. Most of the progress since the late 1960s has been in fusion research and nuclear weapons phenomenology. The computational facility dedicated to magnetic fusion energy (MFE) has critically advanced understanding of magnetic-confinement systems and of fusion and basic plasma processes. The establishment, in 1979, of NASA's theory program in solar-terrestrial plasma physics made numerical models and simulations regular tools in solar-system plasma research and has prepared that research community for the next, more advanced stage.

The continued development of numerical technology will advance many branches of science. In our own fields, we foresee that many problems of a scale that requires today's national computing facilities will soon be addressable by local university and laboratory facilities. This will only increase the importance of numerical modeling to our subjects. Nonetheless, we believe that the leading research on many of the models discussed above will continue to be done on the most advanced computing facilities existing at any given time, because these models involve a complex interplay between large- and small-scale processes.

Thus far, the responsibility for the maintenance and advancement of state-of-the-art computing facilities has been a national one, because it is beyond the capability of single institutions and because a national scope provides an adequate pool of users. America's existing advanced computational facilities, devoted to defense, fusion research, and meteorology, have been used on a piecemeal basis for space and astrophysics problems. These busy facilities do not have space physics and astrophysics as an institutional objective, and researchers in these fields must make individual agreements to secure access to advanced computing. In some cases, American researchers have had to journey to Europe or Japan in order to perform large-scale computations.

In view of the arguments above, and in view of the many space and astrophysical systems ready for systematic modeling:

*We recommend a national computational program dedicated to basic plasma physics, space physics, and astrophysics, which will provide and maintain state-of-the-art technology appropriate to large-scale theoretical models and simulations. Such a program should ensure ready access to advanced computing on the basis of peer review.*



We estimate that present U.S. expenditures on space plasma computing are about \$2 million to \$3 million per year. About \$1 million per year is provided by the National Science Foundation (NSF), and a large fraction of NASA's approximately \$2.2 million per year solar-terrestrial theory budget is devoted to numerical modeling. A somewhat smaller sum is spent on astrophysical modeling. The effort represented by these expenditures provides a reasonable basis on which the more ambitious program that we are proposing could be constructed. Our role has been to point out that a large number of problems central to space and astrophysical plasma research are ready for advanced numerical modeling. If these problems are combined with others in hydrodynamics and general astrophysics that should be included in the program, in a few years the scientific demand, and more importantly, the scientific payoff, will justify the dedicated effort that we propose.

We further recommend that a study be initiated forthwith that would address such issues as the following:

1. The scope and evolution of a national computational program for basic plasma physics, space physics, and astrophysics;
2. The institutional arrangements needed to provide strong scientific guidance to such a program and to ensure ready access to advanced computing on the basis of peer review;
3. The appropriate balance between large-scale and mid-scale computations and between national and local facilities;
4. The ability of existing national facilities to meet the needs of basic plasma physics, space physics, and astrophysics in the near future.

Because problems in magnetic fusion are similar to those in space physics and astrophysics, the experience with the MFE-dedicated facility may prove valuable in considering the questions above. Because the National Center for Atmospheric Research deals with large-scale hydrodynamic calculations, its experience may be equally useful.

## **THE ROLE OF PLASMA PHYSICS IN THE UNIVERSITY CURRICULUM**

### **Space Plasma Physics**

Studies of the space sciences are at present concentrated in a few major institutions and a somewhat larger number of smaller schools. For example, approximately 75 percent of graduate students in solar-

terrestrial physics and the related field of aeronomy are enrolled in 24 United States institutions, which graduate 50 to 60 Ph.D.s each year. Within solar-terrestrial research, most students are supported in the subdisciplines of magnetospheric and solar physics. About 25 percent of the students involved in solar-terrestrial research appear to be doing theoretical plasma physics, and a larger fraction uses plasma concepts in the interpretation of experimental data. In aeronomy, which deals with the upper atmospheres and ionospheres of the Earth and other planets, about 15 percent of the graduate students are pursuing plasma-related topics. We believe that these sample figures illustrate the recent emergence of plasma physics as an important conceptual tool in the older fields of solar-terrestrial research and aeronomy.\*

The place of solar-system plasma physics in the teaching curriculum differs from institution to institution. Courses are taught and graduate degrees are granted in Departments of Physics, Astronomy, Physics and Astronomy, Electrical Engineering, Space Sciences, Earth Sciences, and Atmospheric Sciences, among others. The course content and sequence differ from department to department, reflecting the diverse historical origins and motivations for space plasma research. In those few institutions with major programs in both fusion and space plasma research, the two specialties are not always well integrated into a single course curriculum.

We view the current fragmentation of the space plasma curriculum with concern but not with alarm. It appears to be a natural stage in the evolution of our new discipline. However, *a more unified plasma-physics curriculum that takes into account the achievements of, and applications to, solar-system and astrophysical plasma physics is an important objective for the immediate future.*

### **Astrophysical Plasma Physics**

Because astrophysical plasma physics has not yet become a well-organized subdiscipline of astrophysics, it is difficult to pinpoint the number of graduate students working in astrophysics who are pursuing plasma research. However, an increasing number of research topics in astrophysics involves the use of plasma concepts wholly or in part. At many universities with graduate programs in astrophysics, including

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\*The figures in this paragraph were compiled by D. S. Peacock, Program Director for Solar-Terrestrial Research at NSF, for a joint European-U.S. Workshop on Space Plasma Physics, held at Hilton Head, South Carolina, September 20-23, 1983.

several with distinguished programs, the teaching of plasma physics is inadequate to prepare students for research in plasma astrophysics.

Because the role of plasma physics in astrophysics is destined to grow, this relative lack of university involvement limits both manpower and progress. To the extent that space and astrophysical plasma physics, at the graduate level, are not viewed as integral parts of plasma physics and astrophysics, the intellectual vitality of space science and astrophysics is bound to suffer.

*We recommend that graduate teaching programs in space science and astrophysics include plasma physics as part of their basic course requirements.*

### Plasma Physics in General

The following remarks are meant to apply to all of plasma physics, and the recommendation is directed to colleges and universities whether or not they currently teach plasma physics.

Well-developed scientific disciplines are characterized by deep philosophical motivations, a unified body of powerful theoretical and experimental techniques, and a wide range of applications. It is our conviction that because of the growing integration of space and astrophysics plasma physics with one another, and with laboratory and fusion research, plasma physics is maturing. When a scientific discipline matures, technological innovation soon follows. Plasma physics is only beginning to have its impact.

It is only one generation since plasma physics became a highly developed discipline. During this time, a handful of universities, primarily those with federally funded projects in fusion or space physics, developed graduate programs in plasma physics. Because graduate training in plasma physics is excellent preparation for a variety of careers in science and technology, and in universities, government laboratories, and industry, it is now important to introduce undergraduate students to plasma physics, so that they may make an informed choice of graduate specialty. At present, it is primarily those universities with graduate programs in plasma physics that teach the subject at the undergraduate level.

*In view of the increasing precision of its experimental and theoretical techniques, and in view of its many applications to space physics, astrophysics, and technology, we recommend that plasma physics now become a regular part of the university science curriculum. A one-year junior- or senior-level elective course in plasma physics would be an excellent response to our recommendation.*

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## Glossary

**Ablation.** Removal of material from an imploding pellet by melting and vaporization.

**Accretion.** The process by which mass falls onto a condensed object. The infalling gas is heated to high temperatures as it accretes onto white dwarfs, neutron stars, and black holes. The x radiation from the heated gas provides a characteristic observational signature for these objects.

**Activation.** Process of making a material radioactive by bombardment with neutrons or other nuclear particles.

**Active galactic nuclei.** Active galaxies, which radiate much of their energy, intense continuum, and strong atomic lines in nonthermal forms such as thermal and synchrotron emissions, are observed to generate their power in very small regions called nuclei at their centers. Many astronomers believe that mass accretion onto massive black holes at the centers of active galaxies are responsible for the enormous energy outputs of Seyfert galaxies, radio galaxies, and quasars. It is possible that all galaxies have nuclei that are active to some degree.

**Adiabatic compression.** Compression of plasma not accompanied by gain or loss of heat from the outside. In adiabatic compression, the plasma density and temperature should both increase.

**Air shower.** The shower of energetic particles created when a single cosmic ray or gamma ray collides with the nucleus of an atom in the

upper atmosphere. By studying the number and types of particles created in an air shower, and the particle trajectories, it is possible to infer the energy and, with less accuracy, the direction of arrival of the very-high-energy cosmic-ray primary.

*Alfvén speed.* The characteristic speed of low-frequency waves in conducting magnetohydrodynamic (MHD) fluids. The Alfvén speed is proportional to the magnetic-field strength and inversely proportional to the square root of the mass density. For MHD fluids, the Alfvén speed plays a role similar to the sound speed in ordinary fluids. Named for the Swedish Nobel Laureate, Hannes Alfvén.

*Alfvén waves.* Waves of a much lower frequency than the ion cyclotron frequency, occurring in a plasma or in a conducting fluid immersed in a magnetic field and characterized by a transverse motion of the lines of force together with the plasma.

*Alpha particle.* A positively charged particle made up of two neutrons and two protons bound together; the nucleus of a helium atom. Alpha particles are produced by the deuterium-tritium fusion reaction and serve to sustain the plasma temperature in an ignited fusion reactor.

*Ambipolar diffusion.* Diffusion process in which the electrons and ions escape to the walls at exactly the same rate.

*Ambipolar potential.* An electrostatic potential generated by a plasma to maintain equal loss rates for electrons and ions.

*Anisotropy.* The condition of having different properties in different directions, for example, in the velocity distribution of particles.

*Anomalous transport.* Processes of energy and particle transport in plasmas that generally exceed classical rates and are associated with plasma instabilities and fluctuations.

*ANTARES.* A CO<sub>2</sub>-laser facility in operation at the Los Alamos National Laboratory.

*Antenna.* A device for coupling radio-frequency power to electromagnetic waves that may be launched into a plasma.

*Aspect ratio.* The ratio of the major radius of a torus to the plasma, or minor, radius.

*Aurora, auroras, aurora borealis, auroral zone.* Also known as the northern (and southern) lights, the term aurora refers to light emissions that originate at 100-120 km altitudes above the surface of the Earth. The aurora are typically most frequent between 60° and 70° north and south geomagnetic latitudes. Auroral activity moves equatorward during magnetic storms. Aurora are created when electrons and protons, which can be accelerated to 10 keV or more

in energy at altitudes of 5000-10,000 km, collide with upper-atmospheric neutral atoms.

**Auxiliary heating.** Any form of plasma heating other than the intrinsic (ohmic) heating by the plasma currents themselves. Neutral-beam injection and radio-frequency heating are the most common types of auxiliary heating.

**Ballooning instability.** A mode that is localized in regions of unfavorable magnetic-field curvature and that becomes unstable when the plasma pressure gradient exceeds the local magnetic stress.

**Banana orbit.** An orbit with a banana shape that charged particles can follow in a toroidal magnetic field.

**Barn.** Unit of area used in expressing the cross sections of atoms, nuclei, electrons, and other particles. One barn is equal to  $10^{-24}$  square centimeter. See also *Cross section*.

**Beam-plasma interactions.** A beam of energetic particles injected into a plasma usually loses its energy not by colliding with the plasma particles directly but by exciting collective modes of oscillation of the plasma, which then damp into the energy of plasma particles. The general study of such processes is given the name beam-particle interactions.

**Beta value.** Ratio of the outward pressure exerted by the plasma to the inward pressure that the magnetic confining field is capable of exerting. Equivalent to the ratio of particle energy density to magnetic-field energy density.

**Black holes.** The general theory of relativity predicts the existence of a state of gravitational collapse in which the infalling matter approaches infinite density. Because of the time dilation that occurs in general relativity, the collapse appears to an exterior observer to be nearly frozen. No light can escape to the exterior world from the interior of the object—thus the name black hole. Black holes of stellar mass, thought to be responsible for accreting galactic x-ray sources, have a radius of about 10 km. Black holes in active galactic nuclei have radii of about  $10^9$  km, smaller than the solar system and very much smaller than the surrounding galaxy.

**Blanket.** Region surrounding a fusion reactor core, within which fusion neutrons are slowed down, heat is transferred to a primary coolant, and tritium is bred from lithium.

**Breakeven.** Condition that the fusion power produced in a plasma exceed the power needed to maintain the plasma temperature. For tritium plasmas heated by deuterium beams, the requirements for breakeven are relaxed relative to the Lawson criterion for thermal plasmas. See also *Lawson criterion*.

**Bremsstrahlung.** Radiation emitted as a result of deflection (e.g., through near collisions) of rapidly moving charged particles.

**Brillouin instability.** Decay of an intense laser light wave into a scattered light wave and an ion acoustic wave. Occurs in the low-density plasma surrounding an irradiated target in inertial-confinement fusion.

**Brillouin scattering.** Reflection of electromagnetic radiation from an acoustic-like plasma wave.

**Bumpy torus.** A toroidal configuration created from many canted simple-mirror sectors connected together to form a torus. Stability in the regions of unfavorable magnetic curvature is generally provided by hot mirror-confined electron rings. See also *Elmo Bumpy Torus*.

**Carbon dioxide laser.** A laser that produces intense light pulses in the far-infrared portion of the spectrum, specifically with wavelength of about 10 micrometers. See also *Laser*.

**Central cell.** The main, cylindrical confinement region of a tandem magnetic mirror.

**Cerenkov radiation.** A distinct type of electromagnetic radiation caused by electrons or protons traveling through or near matter.

**Charge exchange.** Process in which there is a transfer of an electron from a neutral atom to a singly charged positive ion, the latter becoming neutral and the former charged.

**Charge neutrality.** Refers to the strong tendency for a plasma to be everywhere free of net electrical charge.

**Classical confinement.** Best possible limiting case for plasma containment. Only rare collisions between particles are considered as the agent that can lead to cross-field losses. It is also referred to as classical diffusion.

**Coherent radiation.** Monochromatic radiation in which all elements of the wave radiate in unison.

**Collective accelerator.** A device in which charged particles are accelerated in the electric and magnetic fields of neighboring charges.

**Collective effects.** Simultaneous interaction of many charged particles, usually through their Coulomb force.

**Collision.** Close approach of two or more particles, atoms or nuclei, during which such quantities as energy, momentum, and charge may be exchanged.

**Collisionless plasma.** A plasma in which the density is so low, or temperature so high, that close binary collisions have practically no significance, because the time scales of interest are smaller than the collision time.



**Collisionless shock waves.** A supersonic airplane creates a shock wave, which causes the familiar sonic boom. The dissipation for ordinary gas-dynamic shocks is due to collisions between gas particles. High-temperature plasmas are collisionless. The dissipation for shock waves in collisionless plasmas is created by microscopic collective plasma modes excited in the shock front.

**Compact toroid.** A toroidal confinement configuration utilizing poloidal magnetic fields but no externally produced toroidal field. Its compactness arises from the absence of toroidal field coils linking the doughnut-shaped plasma.

**Confinement parameter.** The product of number density and energy confinement time of a plasma. See also *Lawson criterion*.

**Controlled thermonuclear fusion.** Process in which very light nuclei, heated to a high temperature in a confined region, undergo fusion reactions under controlled conditions, with the associated release of energy that may be harnessed for useful purposes.

**Corona.** In inertial confinement fusion, refers to the low-density plasma surrounding the irradiated target. In the Sun, it refers to the outermost layer composed of hot, tenuous plasma. See also *Solar corona*.

**Cosmic rays.** Cosmic rays are energetic electrons, protons, positrons, neutrons, neutrinos, atomic nuclei, and other particles accelerated by cosmic processes. Some cosmic rays, typically below  $10^9$  eV energy, are accelerated at the Sun and in the solar system; those above  $10^9$  eV energy are largely accelerated in our galaxy; those above about  $10^{17}$  eV energy are accelerated outside our galaxy.

**Cosmic rays, elemental and isotopic abundances.** Elemental abundance refers to the abundances of different atomic nuclei in the cosmic radiation. *Nuclear isotopes* refer to atomic nuclei with the same number of protons but differing numbers of neutrons. Studies of these abundances reveal much about the material from which the cosmic rays were accelerated, about how they were accelerated, and the density of galactic material through which they have traveled.

**Cross section.** A measure of the probability that a reaction (nuclear or other) will occur. Usually measured in barns, it is the apparent (or effective) area presented by a target nucleus (or particle) to an oncoming particle.

**Current drive.** The process by which the required toroidal currents are created and maintained in a tokamak. In a conventional tokamak, these currents are maintained for a finite pulse duration by inductive transformer action but then decay. Currents can also be driven

noninductively by radio-frequency waves, in which case they may be maintained indefinitely.

**Cyclotron frequency.** The natural oscillation frequency of a charged particle immersed in an external magnetic field. One mode of oscillation is associated with electron gyrations, the other with ion gyrations.

**Cyclotron radiation.** Radiation emitted at the cyclotron frequency by charged particles in a magnetic field as a result of their natural gyration in that field. Sometimes called synchrotron radiation, especially for very fast particles in which case the radiation is emitted at high harmonics of the cyclotron frequency.

**Cyclotron resonance.** Resonance absorption of energy from an alternating electric field by electrons or ions in a magnetic field when the frequency of the electric field equals the cyclotron frequency.

**Debye shielding.** Departure from the inverse-square law of interaction between point charges caused by the presence of neighboring charges.

**Deuterium.** An isotope of the hydrogen atom with one proton and one neutron in its nucleus and a single orbital electron.

**Deuteron.** The nucleus of a deuterium atom.

**Diagnostics.** Procedure for determining (diagnosis), by one means or another, exactly what is happening inside a plasma during an experiment; also refers to the instruments used for diagnosing.

**Direct conversion.** Generation of electricity by direct recovery of the kinetic energy of the charged fusion reaction products.

**Direct illumination.** Refers to an approach to inertial-confinement fusion in which the target is directly irradiated by laser light.

**Disruption.** A sudden loss of plasma confinement in a tokamak, resulting from inadequate control of kinklike instabilities.

**Divertor.** Component of a toroidal fusion device that provides a magnetic field to divert charged particles in the outer shell of the discharge into a separate chamber where they strike a barrier, become neutralized, and are pumped away. In this way, energetic particles in the outer shell are prevented from striking the walls of the main discharge chamber and releasing secondary particles that would cool the discharge.

**Double layers.** Current-carrying plasmas can create thin layers of strong electric field when the current is sufficiently intense. Since these layers contain sheets of positive and negative charge in close proximity, they have been called double layers. It has been suggested that double layers accelerate the particles responsible for the aurora.

*Drift waves.* Oscillations in a magnetically confined plasma that arise in the presence of density gradients.

*Driver.* A powerful laser or particle beam used in inertial confinement fusion, to impart energy to a pellet, thereby causing it to implode.

*Dynamo processes.* A term used to describe the process by which the energy in turbulent motions is converted to magnetic-field energy in conducting fluids and plasmas.

*Earth's magnetic tail.* The interaction of the solar wind with the Earth's magnetic field creates a long magnetic tail that extends more than 1000 earth radii downstream of the Earth. The north lobe of the tail contains a magnetic field that is directed toward the Earth, and the south lobe contains flux directed away from the Earth. Jupiter's magnetic tail is at least 5 AU long.

*EBT.* See *Elmo Bumpy Torus*.

*ECRH.* See *Electron cyclotron resonance heating*.

*Electromagnetic radiation.* Radiation consisting of electric and magnetic waves that travel at the speed of light and can be transmitted through a vacuum.

*Electron.* Elementary particle with a unit negative electrical charge and a mass very much smaller than that of the proton.

*Electron bunching.* Formation of tight electron clumps in space and time.

*Electron cyclotron resonance heating.* Mode of heating of a plasma by resonant absorption of energy based on waves induced in the plasma at the cyclotron frequency of the electrons or at harmonics of the cyclotron frequency.

*Electron density.* The number of electrons in a unit volume.

*Electron-positron pair plasmas.* Plasmas with very-high-energy densities can contain significant numbers of positrons. Those plasmas that contain only electrons and positrons are called pair plasmas. Pulsars, for example, are thought to generate pair plasmas.

*Electron temperature.* The temperature at which ideal gas molecules would have an average kinetic energy equal to that of electrons in a plasma under consideration.

*Electron volt (eV).* Unit of energy equal to the energy acquired by a singly charged particle in passing through a potential difference of 1 volt.  $1 \text{ eV} = 1.6 \times 10^{-19} \text{ joule}$ . A plasma in which the particles have an average energy of 1 eV has a "temperature" of about 10,000 degrees Celsius.

*Electrostatic plugging.* The use of a positive electrostatic potential in the end cells of a tandem mirror to achieve axial confinement of ions in the central cell.

**Electrostatic potential.** Refers to the ability of a point or region in a plasma to attract or repel charged particles. For example, a region of positive electrostatic potential will attract electrons and repel positively charged ions.

**Elmo Bumpy Torus.** A magnetic fusion concept in which high-beta electron rings produced by microwave heating stabilize a bumpy torus.

**End cells.** See *End plugs*.

**End plugs.** Minimum-B mirror cells at the ends of a tandem mirror, within which mirror action provides the dominant mechanism for confining beam-injected energetic ions, thereby providing a positive electrostatic potential for the confinement of thermal ions in the central cell.

**Energy-confinement time.** Time required for a plasma to lose (via radiation or other loss mechanisms) an amount of energy equal to its average kinetic energy.

**Fertile material.** Nuclide that will convert to fissile material on neutron capture and radioactive decay (e.g., uranium-238 or thorium-232).

**Field-reversed configuration.** A confinement configuration of the compact toroid class that utilizes poloidal magnetic fields only. The configuration is generally formed on rapid, dynamic time scales.

**Fissile material.** Any material fissionable by neutrons of all energies, especially including thermal (slow) neutrons as well as fast neutrons (e.g., uranium-235 and plutonium-239).

**Fluctuations.** Refers to small-scale oscillations in a plasma, usually caused by weak instabilities.

**Flute instability.** See *Interchange instability*.

**Free-electron laser.** A laser that uses free (as opposed to bound) electrons as its active medium.

**Free-electron radiation source.** A source that uses free electrons (from an electron gun, for example) to generate electromagnetic radiation. See also *Free-electron laser* and *Gyrotron*.

**Fusion.** Merging of two light atomic nuclei into a heavier nucleus, accompanied in general by the release of energy.

**Fusion-fission hybrid.** Reactor in which energy is produced by both fusion and fission reactions. A fusion neutron source is typically surrounded by a subcritical blanket containing fissile material. If fertile material is also contained in the blanket, the reactor will produce additional fissile material.

**Gamma rays.** Gamma rays are highly energetic photons with energies exceeding about 50,000 electron volts.

**Geometrical optics.** A calculational technique for following the propagation of electromagnetic waves by tracing the trajectories of rays through a refracting medium, e.g., a plasma. The technique is valid if the wavelength is much shorter than the scale size of the plasma.

**Guiding center.** The average center of rotation of a charged particle in motion in a magnetic field.

**Gyrofrequency.** See *Cyclotron frequency*.

**Gyroradius.** See *Radius of gyration*.

**Gyrottron.** A device for producing microwave energy that utilizes a strong axial magnetic field in a cavity resonator to produce azimuthal bunching of an electron beam. Also called an electron cyclotron maser.

**Heavy-ion beams.** Beams of ions of heavy elements, such as uranium, of gigavolt energies that could be produced in conventional high-energy accelerators and might be used as drivers in inertial-confinement fusion.

**Helical.** Spiraling. Usually refers to the trajectory of a field line or charged particle in a configuration with both toroidal and poloidal magnetic fields.

**Hertz.** Unit of frequency equivalent to one cycle per second.

**Hohlraum.** A hollow chamber containing electromagnetic radiation in thermodynamic equilibrium with the hot chamber walls. In its application to inertial-confinement fusion, the laser light is shone into the hohlraum and converted into x rays that serve as the pellet driver.

**Hybrid reactors.** See *Fusion-fission hybrid*.

**Hydrodynamic efficiency.** In inertial-confinement fusion, refers to the fraction of the absorbed driver energy that is delivered in kinetic energy to the fuel.

**Hydrodynamic instability.** A process in inertial-confinement fusion in which nonuniformities in target irradiation may be unstably amplified by hydrodynamic motions of the target surface. Analogous to the instability that develops when a heavier fluid is supported against gravity by a lighter fluid.

**Hydromagnetic instability.** Instability arising from macroscopic motions of a conducting fluid as a result of its interaction with a magnetic field.

**Hydromagnetics.** See *Magnetohydrodynamics*.

**ICRH.** See *Ion cyclotron resonance heating*.

**Ideal MHD.** Magnetohydrodynamic model for an assumed infinitely conducting plasma.

**Ignition.** The high-temperature conditions at which the energy depos-

ited in a plasma through the fusion process just equals the energy losses.

**Implosion.** A violent inward compression.

**Impurities.** Ions in a fusion plasma of elements other than those of the reacting hydrogenic fuel.

**Inertial confinement.** A dynamic, nonmagnetic plasma confinement scheme that uses compressional inertial forces, e.g., laser radiation compressing a D-T pellet.

**Interchange instability.** The type of hydromagnetic instability in which the plasma interchanges position with the magnetic field; also called a "flute instability," since it would be expected that the interface between the plasma and the magnetic field would become fluted.

**Inverse bremsstrahlung.** A process, inverse to that of bremsstrahlung radiation, in which electromagnetic waves (especially laser light in inertial confinement fusion) are absorbed by collisional deflections of electrons vibrating in the wave fields. Also called bremsstrahlung absorption.

**Ion.** Atom that has become charged as a result of gaining or losing one or more orbital electrons. A completely ionized atom is one stripped of all of its electrons.

**Ion acoustic wave.** A longitudinal compression wave affecting the ion density of a plasma.

**Ion cyclotron resonance heating.** Mode of heating a plasma by resonant absorption of energy based on waves induced in the plasma at the cyclotron frequency of the ions or at harmonics of the cyclotron frequency.

**Ion temperature.** The temperature at which ideal gas molecules would have an average kinetic energy equal to that of the ions in a plasma under consideration.

**Ionization.** Process of removing an electron from a neutral atom, thereby creating an ion.

**Ionosphere (terrestrial, planetary).** Ionosphere refers to a layer of plasma in the upper atmosphere that is maintained by photoionization by solar ultraviolet radiation and by collisions with energetic particles of magnetospheric and solar-system origin. In contrast to magnetospheric plasmas, ionospheric plasmas are collision dominated, since they interact with neutral atmospheric gases.

**Irradiation.** Exposure to radiation.

**Isotope.** One of several species of the same element, possessing different numbers of neutrons (but the same number of protons) in their nuclei.

**JET.** Joint European Torus, a large tokamak that is owned in common by the European communities. It has been built at the Culham Laboratory and is generally comparable with the TFTR.

**JT-60.** Large Japanese tokamak, currently under construction. It is generally comparable with JET and TFTR but will not use tritium plasmas.

**Kilometric radiation.** Beam-plasma interactions in the auroral acceleration region excite radio waves with wavelengths of a few kilometers—thus the term kilometric radiation.

**Kink instability.** Hydromagnetic instability that sometimes develops in a plasma column carrying a strong axial current. The column becomes unstable and undergoes a gross lateral displacement toward the walls of the discharge vessel.

**Klystron.** An evacuated electron-beam tube in which an initial velocity imparted to electrons in the beam results subsequently in density modulation of the beam; used as an amplifier or oscillator for microwave radiation.

**Krypton-fluoride laser.** A laser under development with wavelength of about 0.25 micrometer. See also *Laser*.

**Langmuir wave.** Same as a plasma wave.

**Larmor radius.** See *Radius of gyration*.

**Laser.** A device that utilizes the natural oscillations of atoms or molecules between energy levels for generating intense, coherent electromagnetic radiation in the ultraviolet, visible, or infrared regions of the spectrum.

**Laser fusion.** Nuclear fusion process that occurs when a small pellet of fuel material is compressed by a burst of laser light. See also *Inertial confinement*.

**Laser pumping.** Use of electron beams or the radiation from intense light sources, for example, to invert the population of lasing materials.

**Lawson criterion.** Condition that the product of number density and confinement time of a plasma (confinement parameter) must equal approximately  $10^{14}$  cm<sup>3</sup>-s at a temperature of about 70,000,000 degrees to produce net power in a fusion reactor.

**Light-ion beams.** Beams of protons, lithium, or carbon ions of a few megavolt energies, generated by pulsed power accelerators and to be used as drivers in inertial-confinement fusion.

**Light-ion fusion.** Inertial fusion concept using light ions (e.g., protons).

**Limiter.** A mechanical structure placed in contact with the edge of a

confined plasma, which is used to define the shape of the outermost magnetic surface.

*Linear waves.* Small electromagnetic perturbations about the plasma equilibrium state of a plasma.

*Loss cone.* In the velocity space related to a magnetic mirror, the cone having an axis of symmetry parallel to the magnetic field and an apex angle inversely proportional to the square root of the mirror ratio. Particles whose velocity vectors lie in the loss cone will not be reflected by the mirror. This concept is also used for describing the distribution of particles confined in the dipole magnetic-field geometry of the magnetosphere.

*Loss-cone instabilities.* Microinstabilities, occurring primarily in the end cells of magnetic mirrors, driven by anisotropies in the ion velocity-space distribution function caused by the escape of some particles through the loss cones.

*Lower hybrid.* A resonance in a magnetized plasma that involves aspects of both parallel bunching, characterized by the plasma frequency, and perpendicular particle motion, characterized by the cyclotron frequency. The lower-hybrid resonance frequency is intermediate between the electron and ion cyclotron frequencies. Lower-hybrid waves can be used to heat plasmas by absorption at the lower-hybrid resonance.

*Macroscopic instability.* Long-wavelength, low-frequency instability causing major disruption of the plasma profiles.

*Magnetic bottle.* Magnetic field used to confine a plasma in controlled fusion experiments.

*Magnetic confinement.* Use of magnetic fields to contain a plasma.

*Magnetic-field reconnection.* See *Reconnection*.

*Magnetic inculation.* Use of magnetic fields to prevent charges from coming in contact with material surfaces.

*Magnetic island.* A localized magnetic structure within which the field lines are disconnected from those in the main, outer part of the magnetic configuration.

*Magnetic mirror.* Magnetic field that is generally axial, with a local region of increased intensity causing convergence of the field lines. A particle moving into the region of converging magnetic field lines will be reflected unless the ratio of its energy parallel to its energy perpendicular to the magnetic field is too high.

*Magnetic-mirror confinement.* If the magnetic-field strength increases toward both ends of a magnetic field line, charged particles can bounce back and forth along the field line between the regions of strong magnetic field. Such particles are said to be confined in a



magnetic mirror. The Earth's magnetic-field mirror confines the energetic particles of the Van Allen radiation belts; the particles bounce between mirror points in the northern and southern hemispheres. Magnetic-mirror-confinement studies are a prominent part of controlled-fusion research.

*Magnetic pressure.* The pressure that a magnetic field is capable of exerting on a plasma, which is equivalent to the energy density of a magnetic field.

*Magnetic storm.* The term magnetic storm originally referred to large variations in the Earth's magnetic field, and in the position and intensity of the aurora, that occurred several days after large solar flares. The term now applies to the entire sequence of events in the Earth's magnetosphere following the arrival of a flare-generated shock wave at Earth.

*Magnetic well.* See *Minimum-B configuration*.

*Magnetic tail.* See *Earth's magnetic tail*.

*Magnetohydrodynamics (MHD, hydromagnetics).* Magnetohydrodynamics is the simplest theoretical description of the dynamics of a magnetized plasma. It characterizes the plasma as a highly conducting fluid of a given density and pressure, averaging over the distribution of velocities of the electrons and ions. MHD is the primary theoretical tool used to describe the large-scale behavior of plasma systems.

*Magnetopause.* The outer boundary of a magnetosphere—typically a thin layer across which the properties of the plasma and magnetic field change discontinuously. Beyond the Earth's magnetopause, the plasma behavior is controlled by the solar wind.

*Magnetosonic waves.* Waves of frequencies comparable with, or lower than, the ion cyclotron frequency, occurring in a plasma immersed in a magnetic field and characterized by compression of the plasma transverse to the field. Used in ion cyclotron resonance heating.

*Magnetosphere.* The plasma atmosphere of a magnetized central body. The magnetosphere is defined to be the region where the plasma dynamics is controlled by its interaction with the parent body's magnetic field. The outer boundary of the magnetosphere is called the magnetopause.

*Magnetospheric substorms.* See *Substorms*.

*Marx generator.* High-voltage, high-current accelerator in which the voltage multiplication is achieved by charging capacitors in parallel and discharging them in series. A major power source for inertial-fusion systems.

*Microinstabilities.* Small-scale plasma instabilities leading to fluctuations and anomalous transport.

*Micrometer.* A unit of length used to measure very short distances, such as the wavelength of laser light. One micrometer equals  $10^{-6}$  meter.

*Microscopic instability.* Short-wavelength, high-frequency instability causing fine-grained plasma perturbations and turbulence.

*Microwaves.* Electromagnetic radiation with a wavelength of a few centimeters or less.

*Minimum-B configuration.* Name given to a magnetic configuration that increases everywhere in strength with increasing distance from the plasma that it is confining. In such a configuration, the plasma finds itself in a region of minimum magnetic potential and is highly stable.

*Minimum-energy state.* Refers to the condition in which a dynamical system, such as a plasma, is in a configuration of minimum potential energy and is therefore highly stable.

*Mirror.* See *Magnetic mirror*.

*Mirror ratio.* In a magnetic-mirror configuration, the ratio of the strength of the magnetic field at the strongest point on its axis to the weakest field strength between the two magnetic mirrors.

*Monte Carlo method.* A statistical technique for computing the motion of a large number of individual particles.

*Negative-ion beams.* An advanced form of neutral injection in which negative hydrogenic ions (i.e., with excess electrons) are used. The neutralization efficiency, after acceleration to very high energies, is superior to that of positive ions.

*Neoclassical.* Term used to characterize classical-like collisional diffusion in finite toroidal geometries, where geometrical effects enhance the transport relative to an infinitely long straight system.

*Neodymium-glass lasers.* A laser that produces intense light pulses in the near-infrared portion of the spectrum, specifically with a wavelength of about 1 micrometer. See also *Laser*.

*Neutral-beam heating.* See *Neutral injection*.

*Neutral injection.* A technique for heating plasmas in which hydrogenic ions are accelerated to high energies, neutralized, injected across the magnetic field of a confinement device, and subsequently ionized by the plasma inside the magnetic container.

*Neutron.* Uncharged elementary particle with mass about the same as that of the proton and found in the nucleus of every atom heavier than hydrogen. The energy from fusion reactions appears mainly in the form of energetic neutrons.

*Neutron star.* A condensed star that is stabilized against gravitational collapse by the pressure of degenerate nucleons, which are as tightly packed as quantum-mechanical law allows. The centers of large neutron stars are composed primarily of neutrons, with a slight admixture of electrons and protons, whereas the outer layers are an exotic metal composed of neutron-enriched nuclei. Neutron stars are believed to have superstrong magnetic fields. All pulsars are neutron stars, and some galactic x-ray sources are due to mass accretion onto a neutron star from a binary companion star.

*Nonlinear.* Refers to waves and instabilities that have reached amplitudes at which the disturbances are no longer a small perturbation of the equilibrium.

*Nonlinear wave.* Large electromagnetic perturbation about the plasma equilibrium state.

*Nonneutral plasma.* Plasma composed of a single charged species that is not electrically neutralized by a second species.

*NOVA.* A neodymium-glass laser facility under construction at the Lawrence Livermore National Laboratory. Also, the result of explosion of a star with a mass of about one solar mass.

*Nucleosynthesis.* Nucleosynthesis refers to the processes by which all elements of the periodic table, except hydrogen and helium, are created by nuclear burning in stellar interiors.

*Numerical models (fluid, MHD, hybrid, kinetic).* Numerical models of plasma dynamics can be created at both the fluid and kinetic levels of description. Fluid models solve the equations of fluid dynamics, and MHD models solve the corresponding magnetohydrodynamic equations for magnetized, conducting fluids. Kinetic models follow the motions of the individual electrons and ions in the self-consistently calculated electric and magnetic fields of the plasma. Hybrid models treat the ions kinetically and the electrons as a fluid.

*Ohmic heating.* Heating resulting from the resistance a medium offers to the flow of electric current. In plasmas subjected to ohmic heating, ions are heated almost entirely by transfer of energy from the hotter electrons. Also called Joule heating.

*Open system.* See *Magnetic mirror*.

*PBFA II.* Particle Beam Fusion Accelerator II, a light-ion beam accelerator to be used in inertial-confinement fusion, under construction at Sandia National Laboratories.

*Parametric decay.* Decay of one wave into two other waves. For example, decay of an intense laser light wave into a plasma wave and an ion acoustic wave.

*Parametric instability.* Instability that occurs in a system whose

equilibrium is weakly modulated in time or space. The modulation produces a coupling of the linear modes of the unmodulated system and can lead to destabilization. Interaction between three waves, one of which (the pump) feeds energy to the other two.

*Particle ring.* A configuration of the compact toroid class that utilizes energetic ion or electron rings to create a field-reversed configuration.

*Photons.* The quanta of electromagnetic radiation.

*Pinch effect.* Constriction of a plasma column carrying a large current, caused by the interaction of that current with its own encircling magnetic field.

*Pitch angle.* The angle that a particle's velocity vector makes with the direction of the magnetic field. See also *Loss cone* and *Pitch-angle scattering*.

*Pitch-angle scattering.* A charged particle has a helical orbit in a uniform magnetic field. The pitch of the helix is called the particle's pitch angle, which is determined by the ratio of the components of the particle's velocity parallel and perpendicular to the direction of the magnetic field. When two particles collide, or one particle interacts with a plasma wave, the pitch angles are changed or scattered. Pitch-angle scattering leads to losses of mirror-confined particles in the Earth's radiation belts and in fusion devices.

*Plasma.* Ionized gaseous system, composed of an electrically equivalent number of positive ions and free electrons, irrespective of the presence of neutral particles; in view of its prevalence throughout the universe, sometimes called the fourth state of matter.

*Plasma confinement.* Operation intended to prevent, in an effective and sufficiently prolonged manner, the particles of a plasma from striking the walls of the container in which the plasma is produced.

*Plasma cross section.* Refers to the shape of the cross section formed by cutting a doughnut-shaped toroidal plasma.

*Plasma equilibrium.* Plasma system in which there is an overall quasi-steady balance of forces.

*Plasma frequency.* Natural frequency of oscillation of a plasma, caused by the collective motion of the electrons acting under the restoring force of their space-charge attraction to the relatively stationary ions.

*Plasma instability.* State of a plasma in which a small perturbation amplifies, resulting in an alteration of the equilibrium of the system.

*Plasma radiation.* Electromagnetic radiation emitted from a plasma, primarily by free electrons undergoing transitions to other free states

or to bound states of atoms and ions, but also by bound electrons as they undergo transitions to other bound states.

**Plasma wave.** A disturbance of a plasma involving oscillation of its constituent electrons at the plasma frequency. The term plasma wave is often used more generally to denote collective modes of oscillation in a plasma.

**Polarization.** All electromagnetic radiation can be characterized by its frequency and the direction in which the electric field of the electromagnetic waves oscillates. When the electric field averaged over time takes on all possible directions (relative to the direction of propagation of the radiation), the radiation is said to be unpolarized. When the electric field has a preferred direction, or when its direction rotates coherently, the radiation is polarized. The synchrotron process, for example, generates polarized radiation.

**Poloidal divertor.** A divertor that takes out poloidal magnetic field lines, forming a separatrix in the poloidal field. See *Divertor*.

**Poloidal field.** A magnetic field that encircles a toroidal plasma the short way around. See also *Toroidal field*.

**Ponderomotive force.** Radiation pressure exerted by an electromagnetic wave on charged particles.

**Positron.** The laws of quantum electrodynamics allow the existence of a particle conjugate to the electron, which has the same mass as the electron but the opposite (positive) charge.

**Proton.** Elementary particle with a single positive electrical charge and a mass more than 1800 times larger than that of the electron; the nucleus of an ordinary hydrogen atom.

**Pulsars.** Rapidly spinning magnetized neutron stars that generate beams of electromagnetic radiation, usually radio emissions, in their rotating magnetospheres. These emissions are detected as periodically spaced pulses that repeat at the spin frequency of the parent neutron star.

**Pulse power system.** High-current, high-voltage accelerator that produces short energy bursts by pulse compression.

**Pumped limiter.** An advanced form of mechanical limiter, containing channels through which neutral gas formed by plasma recombination can be pumped away. See also *Limiter*.

**Quasars.** Quasars appear as unresolved starlike images on astronomical photographic plates. However, the spectrum of the radiation that they emit is strongly red shifted, indicating that they are enormously powerful objects located at great distances from our galaxy. Many theoreticians believe that quasars derive their huge luminosity from

accretion onto a massive black hole at the center of an otherwise normal galaxy.

*RFP.* See *Reversed-field pinch*.

*Radar backscatter.* The velocity distributions of the particles that make up a plasma, and the collective fluctuations in the plasma, may be diagnosed by directing a beam of electromagnetic radiation at the plasma and analyzing the backscattered signal. Radar beams backscattered from the ionosphere have provided valuable information about ionospheric plasmas.

*Radiation.* Emission and propagation of energy by means of electromagnetic disturbances that display wavelike behavior. See also *Plasma radiation*.

*Radio-frequency heating.* A technique for heating plasmas by the absorption of the energy contained in electromagnetic waves launched by an antenna or waveguide into the containment vessel. Various types of radio-frequency oscillators can provide the power sources for such techniques.

*Radio galaxies.* That class of active galaxies that radiate significant quantities of energy in the form of radio emissions. A typical radio galaxy has twin emission lobes aligned along a line that passes through the center of the parent galaxy.

*Radius of gyration.* For a charged particle moving transversely in a uniform magnetic field, the radius of curvature of the projection of its path on a plane perpendicular to the field. Also known as the Larmor radius.

*Raman instability.* Decay of an intense laser light wave into a scattered light wave and a plasma wave. Occurs in the low-density plasma surrounding an irradiated target in inertial-confinement fusion.

*Ray tracing.* See *Geometrical optics*.

*Rayleigh-Taylor instability.* See *Hydrodynamic instability*.

*Reconnection.* That class of plasma processes by which magnetic-field topologies—which would be stable in MHD—change owing to collisional or collective dissipation. The simplest case is a plane neutral sheet in which the magnetic field lines are oppositely directed above and below the neutral layer, where the magnetic field is zero. Reconnection causes the originally oppositely directed field lines to pass through the neutral sheet and connect to one another. Reconnection converts magnetic energy into particle energy.

*Refraction.* Bending of oblique incident rays as they pass from a medium having one refractive index into a medium having a different refractive index.

**Relativistic particles.** Classical Newtonian mechanics becomes invalid for particle velocities approaching the speed of light, where Einstein's theory of relativity must be used. Particles whose velocities are close to the speed of light are said to be relativistic.

**Resistive instability.** Instability resulting from macroscopic motion of a plasma with a finite electric conductivity. Resistive instabilities are generally much weaker than hydromagnetic instabilities.

**Resistive MHD.** Magnetohydrodynamic model that allows for finite plasma resistivity.

**Reversed-field pinch.** A toroidal configuration that utilizes the pinch effect to confine a plasma carrying a large toroidal current and provides stability against kink and interchange modes by introducing a relatively weak, externally imposed toroidal magnetic field that reverses its direction at the edge of the plasma.

**Rotational transform.** A toroidal magnetic-field configuration is said to possess rotational transform if the lines of force, after one circuit around the configuration, do not close exactly on themselves but are rotated through some angle called the rotational transform angle.

**Safety factor.** The inverse of the rotational transform of a toroidal magnetic-confinement system. In a tokamak, the value of the safety factor must exceed unity to avoid kink instabilities.

**Scattering.** Deflection of one particle as a result of collisions with another.

**Second stability regime.** Refers to a regime of toroidally confined plasmas that is free from ballooning instabilities at arbitrarily large beta values.

**Separatrix.** A magnetic surface that separates regions of closed field lines from regions of open field lines.

**Solar corona.** The solar corona is the tenuous, outermost plasma atmosphere of the Sun. It is heated to a temperature of about 1 million kelvins and extends to a distance of several solar radii from the optical surface (photosphere) of the Sun. It ultimately blends into the solar wind.

**Solar coronal holes.** Solar coronal holes are open magnetic-field configurations in which the corona in the solar wind is generated. Since the plasma inside the open configuration is cooler than in the surrounding corona, it emits less x radiation. Thus, the open regions appear as holes in generally bright x-ray photographs of the Sun.

**Solar coronal loops.** Closed magnetic structures in the solar corona, which take the characteristic form of loops emerging from the visible surface of the Sun.

**Solar flare.** A solar flare is believed to be triggered by the rapid

conversion of magnetic to particle energy in the solar corona. Strong flares generate intense radio, optical, and x-ray emissions and launch strong shock waves in the solar wind that propagate throughout the solar system.

*Solar photosphere.* The outermost layer of the Sun, as observed in optical light. It is the region from which most of the Sun's optical photons escape into space.

*Solar (stellar) chromosphere.* A thin layer between the photosphere and corona, in which atomic spectral lines can be observed in emission rather than absorption.

*Solar-terrestrial physics.* The study of the chain of processes, almost all of which involve plasma physics, that links the generation of the Sun's magnetic field deep inside the Sun, solar surface and coronal magnetic activity, generation of the solar wind, the dynamics of the Earth's magnetosphere, and the Earth's ionosphere and upper atmosphere.

*Solar wind.* A supersonic, super-Alfvénic plasma wind that is generated in open magnetic structures in the solar corona (solar coronal holes) and streams throughout interplanetary space.

*Soliton.* Large-amplitude wave pulse that preserves its amplitude and shape.

*Space charge.* Local electric fields through which charged particles interact.

*Spheromak.* A confinement configuration of the compact toroid class that utilizes toroidal and poloidal magnetic fields of comparable magnitude but differs from the tokamak and reversed-field pinch in that the toroidal field is produced entirely by currents within the plasma. The configuration is generally formed by quasi-static inductive techniques.

*Stellarator.* A toroidal confinement configuration that uses the combination of a toroidal magnetic field and an additional field created by helical windings. This magnetic configuration provides a rotational transform in itself and permits containment in the absence of an axial current in the plasma.

*Strongly coupled plasma.* Dense plasma in which the electrical energy is comparable in magnitude with the particle kinetic energy.

*Substorms.* Rapid flow reconfigurations of the Earth's magnetosphere, which are thought to be induced by changes in the direction of the solar-wind magnetic field and triggered by reconnection in the magnetic tail. Substorms greatly intensify the aurora in the upper atmosphere.

*Sunspot.* Cool dark regions observed optically in the solar



photosphere. Sunspots contain concentrations of strong magnetic fields that connect to the corona above the photosphere and to the solar convection zone below.

*Super-Alfvénic.* A plasma flow speed that exceeds the speed of an Alfvén wave.

*Superconductor.* Type of conductor that permits an electrical current to flow with zero resistance. Superconducting coils are expected to be used as electromagnets in most types of fusion reactors.

*Supernova.* An explosion of an entire star.

*Supernova remnant.* The remains of a star's outer layers that are observed to expand at high speeds outward into space following a supernova explosion.

*Superthermal electrons.* Electrons in a plasma that have been accelerated by dc or fluctuating electric fields to energies much greater than the average thermal energy, or temperature, of the plasma.

*Synchrotron radiation.* Relativistic particles in a magnetic field emit a broadband continuous spectrum of synchrotron radiation, which was first observed in high-energy particle accelerators, called synchrotrons.

*Tandem mirror.* A magnetic-mirror configuration in which two minimum-B mirror cells are used to plug the ends of a much larger, cylindrical central mirror cell.

*Target.* In inertial-confinement fusion, refers to the pellet of D-T fuel that is to be imploded by the laser light or particle beam.

*Tearing instability.* Resistive instability that grows at a rate slower than the MHD rate but faster than the skin diffusion rate. The instability tears poloidal field lines and reconnects them into a new state of lower magnetic energy.

*Terrella.* Terrella means little Earth. The term is used to refer to laboratory experiments designed to simulate the interaction of the solar wind with the Earth's magnetosphere, in which a high-speed flowing plasma is directed toward a dipole magnetic field.

*TFTR.* Tokamak Fusion Test Reactor, a large toroidal device at Princeton Plasma Physics Laboratory operating as a standard tokamak capable of modest adiabatic compression. In addition to operating as a hydrogen experiment, it will be capable of injecting high-energy neutral deuterium into a tritium plasma, thereby producing a D-T plasma under breakeven reactor conditions.

*Thermal barrier.* Regions, located between the central cell and the end plugs of a tandem mirror, in which the electrostatic potential is driven negative by local electron heating and which serve to isolate the electrons in the central cell from those in the end plugs, thereby

increasing the efficiency with which the positive electrostatic plugging potentials can be maintained.

*Thermal conductivity (diffusivity).* Quantities that measure the rate at which energy (heat) can be transported across (or along) the magnetic field in a plasma with a temperature gradient.

*Thermonuclear burn.* The process in which alpha particles from D-T fusion reactions can sustain the plasma temperature, thereby prolonging the reacting conditions until much of the D-T fuel is consumed.

*Thermonuclear conditions.* Achievement of an adequately confined plasma having temperature and density sufficiently high to yield significant release of energy from fusion reactions.

*Tokamak.* Name given to a specific magnetic-field geometry in controlled fusion, involving confinement and heating of a plasma in a toroidal configuration. A large current induced in the plasma provides the rotational transform necessary for confinement while simultaneously heating the plasma.

*Toroidal confinement.* Name given to the general class of doughnut-shaped magnetic fields in which lines of force close on themselves. Stellarators, tokamaks, and reversed-field pinches are examples of this class of devices.

*Toroidal field.* The main confining magnetic field, which encircles a toroidal plasma the long way around. See also *Poloidal field*.

*Toroidal-field coils.* Coils in a toroidal system that provide the main confining field. Each turn completely surrounds the minor axis of the plasma.

*Torsatron.* A modification of the stellarator concept, in which both toroidal and poloidal fields are generated by helical windings alone.

*Transmission line.* High-voltage coaxial system used to transmit high-voltage pulsed currents from the accelerator to the plasma target.

*Trapped-particle instability.* Slowly growing class of instabilities driven by particles that cannot circulate freely in a toroidal system.

*Trapped particles.* Those particles in a toroidal configuration that are unable to circulate freely around the torus but are reflected from regions of relatively high field, as in a magnetic mirror. The term also applies to particles trapped in the Earth's dipole field.

*Tritium.* An isotope of the hydrogen atom with one proton and two neutrons in its nucleus and a single orbital electron.

*Triton.* The nucleus of a tritium atom.

*Turbulence.* Random mixing of large electromagnetic perturbations.

*Velocity space instability.* A class of instabilities driven by particle distributions that are not in thermal equilibrium

*Waveguide.* A device for transmitting relatively short-wavelength electromagnetic waves into a plasma-containment vessel.

*Wavelength.* The length of a wave measured from one point to the corresponding point on the next wave, usually measured from crest to crest.

*Wave-particle interactions.* The interactions between particles and collective modes of oscillation (waves) in a plasma are wave-particle interactions. These lead to much more dissipation than do collisions, when the plasma temperature exceeds about 10,000 kelvins.

*X ray.* A form of electromagnetic radiation emitted either when the inner orbital electrons of an excited atom return to their normal state or when a metal target is bombarded with high-speed electrons.

*Z-pinch.* Plasma that pinches because of high electrical currents and self-magnetic fields.

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